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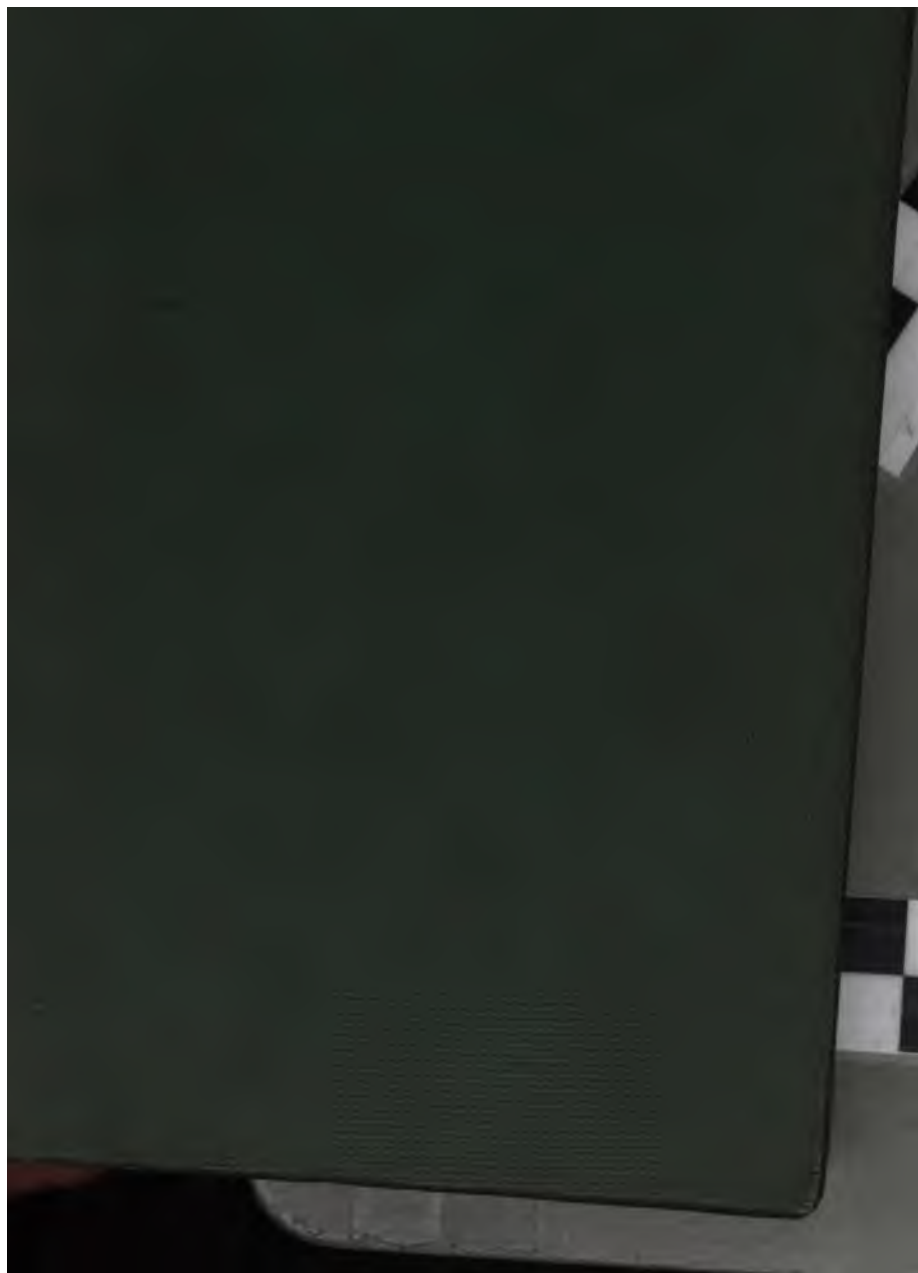
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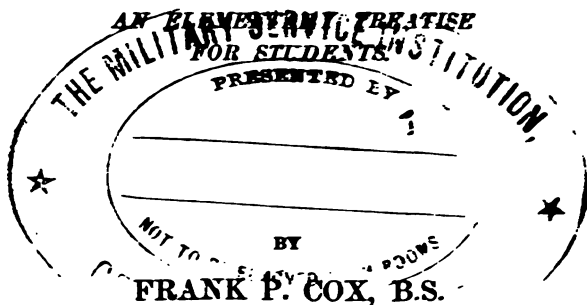
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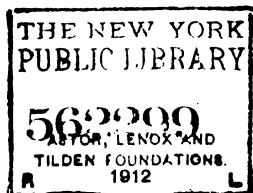
# CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

THEIR THEORY, DESIGN AND TESTING.

WITH SECTIONS ON INDICATOR DIAGRAMS, PROPERTIES OF  
SATURATED STEAM, BELTING CALCULATIONS,  
ETC., ETC.



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ROY WEN  
DUBIN  
VIRGIL

## PREFACE.

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IN placing this work before the public it is not claimed that any new theory of the action of direct-current dynamos and motors has been evolved. Standard authors have been freely consulted, but not copied. It is assumed that the student has a general knowledge of electricity and is conversant with the names of the different parts of the machines. No particular machine has been described, the work being a general consideration of the laws governing the design of direct-current dynamos and motors.

The first four chapters consist of a brief review of the electrical units and the general principles of the machines, and may be considered as an introduction to the subsequent portions. The higher branches of mathematics have been avoided and a knowledge only of algebra and the elements of geometry assumed.

It is hoped the work will prove of value to the student of electricity and to those called upon to design electrical machines who have not had the benefit of a thorough training in the science of electricity. It is needless to say that it is *not* intended for scien-

tists or physicists, who may obtain their knowledge from more advanced treatises and to whom an elementary treatise would be of no service. It will, it is hoped, give evidence that theory and practice are not so far separated as some so-called practical electricians would have us believe, and that the actions of a dynamo may be calculated with considerable accuracy before the machine is built.

Although intended primarily for a consideration of dynamos and motors, the last two chapters are devoted to the actions of steam in an engine. This subject is one so closely allied to the testing and operation of dynamos and motors that it should not be neglected.

An appendix on testing of iron and one upon belting have been included. In general it may be assumed that the subjects treated, if they do not concern the dynamo or motor directly, have so important an influence on their design or testing that they could not be omitted without considerable injury to the value of the work.

FRANK P. COX.

August, 1893.

# CONTENTS.

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## CHAPTER I.

	PAGE
<i>The Absolute System of Measurement</i> :—The metric system. Fundamental and derived units. Lines of force. Ohm's law . . . . .	7-21

## CHAPTER II.

<i>Electro-magnetic Induction</i> :—Current induction and direction of flow. The function of the commutator . . .	22-36
---	-------

## CHAPTER III.

<i>Classification of Machines and General Principles of the Magnetic Circuit</i> :—Drum and ring armatures. Open and closed coil armatures. Series, shunt, and compound-wound machines. Single magnetic-circuit and consequent-pole machines. Effect of the armature current .	37-51
--	-------

## CHAPTER IV.

<i>The Dynamo as a Motor</i> :—Direction of rotation. Counter-electromotive force. Classification of machines. Effect of armature current . . . . .	52-60
---	-------

## CHAPTER V.

	PAGE
<i>Calculations pertaining to the Magnetic Circuit</i> :—Table of symbols. Kapp's method. Line integral of magnetic force. Hopkinson's method . . . . .	61-83

## CHAPTER VI.

<i>Theory of Windings, Losses, etc.</i> :—Generation of potential difference. Determination of series windings. Iron losses. Efficiency. Series, shunt, and compound-wound machines . . . . .	84-100
---	--------

## CHAPTER VII.

<i>The Dynamo as a Motor</i> :—Energy developed. Equations of torque and speed. Series, shunt, and compound-wound motors . . . . .	101-123
--	---------

## CHAPTER VIII.

<i>Design of Armatures</i> :—Determination of the induction, dimensions of core, windings, losses, etc. Siemens and Gramme armatures . . . . .	123-141
--	---------

## CHAPTER IX.

<i>Design of Field Magnets</i> :—Determination of the induction, dimensions of field-cores, poles, yokes, and windings. Single magnetic-circuit, consequent-pole, and multipolar fields . . . . .	142-160
---	---------

## CHAPTER X.

<i>Design of Motors</i> :—Efficiency, torque, and energy developed	161-168
--	---------

## CHAPTER XI.

<i>no and Motor Testing</i> :—Characteristic curve. Saturation curve. Speed curve. Potential curve. Losses. Ing. Motor curves . . . . .	169-184
---	---------

## CHAPTER XII.

	PAGE
<i>Efficiency Tests</i> :—Absorption and transmission dynamometers. Method without dynamometers . . . . .	185-196

## CHAPTER XIII.

<i>Indicator Diagrams</i> :—Reducing motions. Various lines of the diagram. Reading indicator-cards. Determination of clearance. Theoretical curve . . . . .	197-214
--	---------

## CHAPTER XIV.

<i>Steam-engine Calculations</i> :—Horse-power developed. Engine constant. Generation of steam under constant pressure and under constant volume. Efficiency. Duty of boilers . . . . .	215-230
---	---------

## APPENDIX I.

Tests on Iron . . . . .	231-243
-------------------------	---------

## APPENDIX II.

Ampere turn-table . . . . .	244-251
-----------------------------	---------

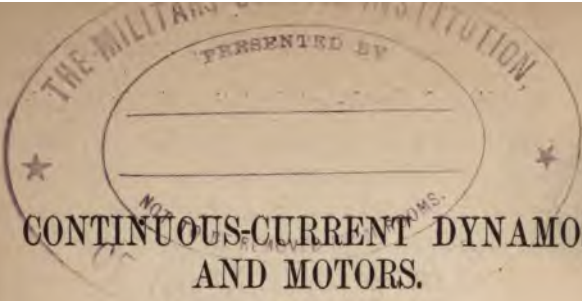
## APPENDIX III.

Determination of sizes of wire for armatures and field coils	252-256
--	---------

## APPENDIX IV.

Belting . . . . .	257-266
-------------------	---------





# CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

## CHAPTER I.

### THE ABSOLUTE SYSTEM OF MEASUREMENT.

In commencing the study of a science a matter of primary importance is the system of measurement employed. In the science of electricity the system is exceedingly simple and is known as the absolute or C. G. S. system, C, G, and S being the initial letters of the three fundamental units, Centimeter, Gram, and Second on which the system is based. It was the intention to compare lengths with some natural magnitude, and accordingly a very accurate survey was made on the meridian passing through Paris. The survey was from Dunkirk, France, to Barcelona, Spain, and from the results the length of the meridional quadrant was computed,  $\frac{1}{10000000}$  part of this distance being considered a meter. Later investigations indicate an error in this length, and for all practical purposes any length could have been taken as a unit. The true length of the meter is therefore not  $\frac{1}{10000000}$  of the

## 8 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

earth's meridional quadrant, but the distance at zero degrees centigrade between two points on a platinum bar in keeping of the Academy of Sciences at Paris.

Having determined the meter, the next step was to express the values of fractions and multiples of this quantity. The decimal system, offering many advantages in the simplification of calculations, was adopted. Thus to reduce a quantity to the same value in the next lower denomination it is only necessary to move the decimal point one place to the right, and similarly to transfer to the next higher denomination move the point one place to the left. The fractions were designated by Latin prefixes, while the multiples were expressed by Greek prefixes. Thus :

Unit.				Unit.
<i>Micro</i> ———	means	$\frac{1}{1000000}$	of a	———
<i>Milli</i> ———	“	$\frac{1}{1000}$	“	———
<i>Centi</i> ———	“	$\frac{1}{100}$	“	———
<i>Deci</i> ———	“	$\frac{1}{10}$	“	———
———	“	1		———
<i>Deka</i> ———	“	10		———
<i>Hecto</i> ———	“	100		———
<i>Kilo</i> ———	“	1000		———
<i>Myria</i> ———	“	10000		———
<i>Mega</i> ———	“	1000000		———

Thus a kilometer is 1000 meters, and a millimeter is  $\frac{1}{1000}$  of a meter. A meter corresponds to 39.37079

inches. The most convenient unit of length is the centimeter, about  $\frac{2}{3}$  of an inch.

The next unit to be considered is the unit of volume. This unit is one cubic centimeter. One liter is equal to 1000 cubic centimeters or about one quart. The same prefixes are used, one hectoliter being equal to 100 liters.

The unit of weight in this system is the gram, and is defined as the weight of a cubic centimeter of distilled water at 4° C.

A gram weighs 15.43235 grains; a kilogram about 2 lbs.

The mean solar second, or briefly the second, is considered as the unit of time. The time required for the earth to make one complete revolution around its axis is a sidereal day. A mean solar second is the time of one swing of a pendulum which makes 86164.1 swings in one sidereal day or 86400 swings in a mean solar day.

We have now the three fundamental units of mass, length, and time, and all other units are derived from these values.

Velocity is the rate of change of position. If a particle move at a uniform speed from one point to another one centimeter distant in one second, it is said to have a velocity of one centimeter per second.

Acceleration is the rate of change of speed. If at any instant a particle has a velocity of one centimeter per

## 10 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

second, and if at the end of one second the velocity is found to be two centimeters per second, the velocity has increased one centimeter per second. That is, it has been accelerated one centimeter per second. It is assumed, of course, that the increase has been at a constant rate. Acceleration is said to be negative when the speed is being diminished, and positive when the speed is being increased. Acceleration is related to velocity in the same manner that velocity is related to position.

If  $v$  represent the velocity of a particle,  $l$  = the distance it has moved in the time  $t$ , then

$$v = \frac{l}{t}.$$

Let  $v_1$  represent the velocity at any instant, and  $v_2$  the velocity  $t_1$  seconds later, and designating the acceleration by  $a$ ,

$$a = \frac{v_2 - v_1}{t_1}.$$

In the first equation  $l$  represents the difference between the two positions of the particle. If in the second equation  $v_2$  represents the difference in the two velocities of the particle,

$$a = \frac{v_2}{t_1},$$

the similarity of the equations is evident.

A body cannot accelerate itself. If a body be mov-

ing at a constant rate, this rate cannot be increased unless some external force is applied to it. Neither can it be diminished unless it is overcoming some external force, such as friction, gravitation, etc., etc. This property of matter is called inertia. Inertia is that property of matter which opposes any change in its condition of motion or of rest. Having now a conception of what a force is, it becomes necessary to have a unit for measuring it.

The dyne is the unit of force. It is that force which, acting upon a mass of one gram for one second, will increase or diminish its velocity one centimeter per second.

The next dynamical conception is that of work. In order to perform work it is necessary that there shall be motion. No matter how great a force is applied to a mass it must move, though ever so little, before work will be performed.

Energy is the capacity for performing work. It exists in a potential state without motion. When motion results work is being done and energy consumed or, rather, transformed. Energy cannot be created or destroyed. It exists in many forms and can be transformed from one to another. There are two kinds of energy, potential energy and kinetic energy. The former is the energy of position; the latter the energy of motion. Work may be defined as motion against resistance.

The unit of work is the erg. It is the work exerted in moving a weight of one gram through a distance of one centimeter against a force of one dyne. Ten million ergs are one joule. This is the practical unit of work, the erg being too small for service.

From work it is but a step to activity. Activity is the rate of performing work. It requires a definite amount of work to raise a given weight to a given height. But the activity or power is not any fixed quantity. It depends upon the time required to perform the work. A certain power will be required to do the work in ten seconds. Ten times that power would be required to do the work in one second. The work is in each case the same, but the activity or power is in one case ten times as great as in the other. The watt is the unit of activity or power, and is the equivalent of ten million ergs per second, or one joule per second.

Before deriving the units of the electro-magnetic system it will be well, perhaps, to briefly consider the nature of magnetism and of the electric current.

The magnet was known to the ancients in its natural form, the loadstone. They observed the difference of polarity, and also noted the repulsion existing between similar poles and the attraction between dissimilar. Beyond this their knowledge did not extend. By far most rational explanation of magnetic action is upon the conception of lines of force. These

lines, like the meridians, are imaginary lines connecting the two poles of a magnet. A free magnet pole placed on any point of a line of force will follow that line to the pole. It will never cross the lines of force. The positive direction of a line of force is from north to south outside the magnet, and from south to north in the body of the magnet. It will be seen, therefore, that every line is a closed curve passing through the two poles of a magnet.

Lines of force are assumed to be imaginary lines, but they can be made visible. If a piece of cardboard sprinkled with iron filings be placed on a straight bar magnet and lightly tapped, the filings will be observed to take position similar to Fig. 1.

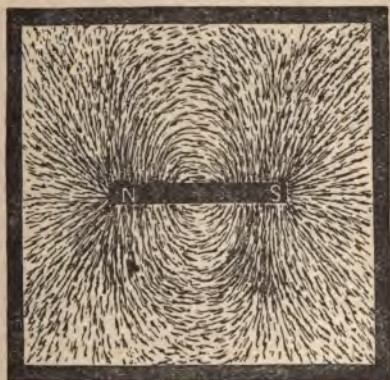


FIG. 1.

The lines of filings should not be confounded with lines of force. For many of the lines seem to break

#### 14 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

off and do not form closed curves. If each line of filings be conceived to be a tube of force made up of a number of lines of force, the broken lines are easily accounted for. A single line of force has not sufficient strength to move the small particle of iron. But the combined action of a number of lines or a tube of force is sufficient, and the iron is moved to its new position. Near the magnet the lines of force are more dense than at a distance, and here the lines of filings are very distinct. At a distance from the magnet the lines are more scattered, are too far apart for their combined strengths to move the particle. Therefore, while the lines of filings break off, the lines of force must be conceived to continue across the gap.

The region around a magnet where these lines of force are found is called the field of that magnet, or, considered apart from the magnet, simply a magnetic field. The strength of a magnetic field is measured by the number of lines of force which exist in a square centimeter of that field. If one line of force passes through *every* square centimeter of the field, the field is called a uniform magnetic field of unit intensity.

A unit field may also be defined as one which acts on a unit magnetic pole with a force of one dyne.

By a unit magnetic pole is meant one which repels or attracts a similar pole placed one centimeter distant with a force of one dyne.

Coulomb has shown by means of his torsion balance that the force acting between two magnetic poles is equal to the product of the strengths of the poles divided by the square of their distance apart. This law will give us a second definition of a unit magnetic pole.

Consider a free magnetic pole of strength  $S$  placed at the center of a sphere of radius  $r$ . The force acting between this pole and one of strength  $P$  placed anywhere on the surface of the sphere is evidently

$$\frac{SP}{r^2}.$$

It is also true that this force is equal at all points on the surface of the sphere. That is, that the surface of the sphere is of uniform density, and there are evidently  $\frac{SP}{r^2}$  lines of force passing through every square centimeter of the surface. The surface of a sphere of radius  $r$  we know from geometry to be  $4\pi r^2$ . Therefore the total number of lines of force passing through the surface of the sphere (and it is evident that this is the number which emanate from the pole  $S$ ) is

$$4\pi r^2 \times \frac{PS}{r^2};$$

or

$$4\pi PS.$$

If the poles are of equal strength, the expression becomes

$$4\pi S^2;$$

and if the poles are of unit strength and  $F$  is the number of lines piercing the surface of the sphere,

$$F = 4\pi.$$

This gives a second definition of a unit pole as "one from which  $4\pi$  lines of force emanate."

An electric current is in some respects similar to a magnet, and is surrounded by lines of force in a somewhat similar manner.

A piece of cardboard is sprinkled with iron filings, and has a wire passed through it at right angles to its plane. When a current of electricity is passed through the wire, the filings arrange themselves in concentric circles around the wire as a center. A free magnet pole placed on one of these lines would tend to circle around the wire, its direction being controlled by the direction of the current. A wire carrying a current is always surrounded by these magnetic whirls.

Except that the wire has increased somewhat in temperature there is no apparent change in its condition when carrying a current. The important effect is in the space surrounding the wire. If, therefore,

lines of force can be created around a wire, a current is created in the wire.

When a wire sweeps across a magnetic field, the lines of force, being elastic, tend to wrap themselves around the wire. But when these lines are created around a wire there will be a current of electricity



FIG. 2.

in the wire. Therefore, by sweeping a wire across a magnetic field a difference of potential or pressure is created between the ends of the wire. This pressure may be compared with the pressure of water. If a pond at the top of a hill be connected by a pipe to one at the base of the hill, a current of water will flow through the pipe. The direction of this flow will be from a high point to a lower one. This difference of pressure in electricity is called potential difference or electromotive force.

The unit of electromotive force is the potential difference between the ends of a wire one centimeter long cutting across a unit magnetic field at the rate of one centimeter per second. This unit would be entirely too small for practical use, and a multiple of it is used. One volt is equal to 100,000,000 C. G. S. units of electromotive force.

The next unit will be that of the flow of current. If a wire be bent in a circle of one centimeter radius, the length of the wire will be  $2\pi$  centimeters. If a current is flowing through the wire, one side of the circle will have a magnetic field of *N* polarity, while the opposite side will have a field of *S* polarity. So far as magnetic effects are concerned, this current could be replaced by a very short bar, having the same diameter as the circle, provided the poles of this short magnet be of suitable strength. This short magnet is called the equivalent magnetic shell for the current. If a unit magnetic pole were suspended in the centre of the coil, it would be acted on by a force proportional to the strength of the current. If the force attracting the unit pole is  $2\pi$  dynes, the current is said to be a unit current.

A unit current of electricity may therefore be defined as one which acts on a unit magnetic pole one centimeter distant with a force of one dyne for every centimeter of wire through which the current flows.

This unit is too large for practical purposes. The practical unit of current is the ampere.

One ampere is  $\frac{1}{10}$  C. G. S. unit of current.

The flow of water through a pipe is retarded by friction, capillary attraction, etc. The flow of a current through a wire also meets with a resistance. This resistance depends upon the material of which the wire is made, and is proportional directly to the length and inversely to the cross-section of the wire. With a given potential and resistance a certain current will always flow. If an electromotive force of one volt forces a current of one ampere through a wire, the wire is said to have a resistance of one ohm. This is the practical unit of resistance, the C. G. S. unit being much smaller. One C. G. S. unit of electromotive force would force one C. G. S. unit of current through one C. G. S. unit of resistance. One ohm equals 1,000,000,000 C. G. S. units of resistance.

These three electrical units are connected by a rule known as Ohm's Law. This law is that current equals electromotive force divided by resistance, or expressing it in an equation,

$$C = \frac{E}{R},$$

where  $C$  = current in amperes,

$E$  = potential difference in volts, and

$R$  = resistance in ohms.

## 20 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

This law may also be written

$$R = \frac{E}{C},$$

and

$$E = CR.$$

These three formulæ are of utmost importance to the electrician. The student is often confused by finding resistance spoken of as a velocity. The explanation is very simple. If a conductor one centimeter long be moved in a unit magnetic field at a velocity of 100,000,000 centimeters per second, one volt of electromotive force will be generated. If the two ends of the conductor be connected through such a resistance that one ampere of current will flow, this resistance is evidently an ohm. Therefore the velocity with which a conductor one centimeter long must move in a uniform magnetic field of unit intensity in order to cause a current of one ampere to flow through a resistance of one ohm is 100,000,000 centimeters per second. But the C. G. S. unit of current is ten amperes, and to cause this current to flow the speed must be ten times as great, or 1,000,000,000 centimeters. Consequently an ohm is sometimes spoken of as an earth quadrant per second.

In moving this conductor across the field a certain *resistance* is overcome. This resistance is propor-

tional to the electromotive force and to the current flowing. If a conductor has its ends joined through a resistance of one ohm, the power expended in generating one volt between the ends of the conductor is one watt. Thus the watt forms a connecting link between electrical and mechanical power.

There is an electrical unit of quantity (the coulomb) which corresponds to quantity of flow in a water-pipe. The definition of a coulomb is that quantity of electricity carried over by one ampere in one second.

There remains but one unit to define, that of capacity. When an insulated conductor has a current of electricity flowing in it, its electrical potential rises. When its potential has risen to one volt higher than the potential of the earth, if there is one coulomb of electricity in the wire, its *capacity is said to be one farad*. If any volume be filled with steam, the amount of steam which it can contain will be doubled if the pressure is doubled. Similarly a condenser will contain twice as much electricity if the potential is doubled. Consequently we may say that the capacity of a condenser is the number of coulombs it contains divided by the pressure in volts.

---

## CHAPTER II.

### ELECTRO-MAGNETIC INDUCTION.

WE have seen (page 18) that when lines of force are created around a wire, a current of electricity is created in the wire. If, therefore, the lines can be caused to circulate around a wire, the problem of current induction will be solved. If a cord be held at one end and struck sharply with a stick near the other end, it will be seen to wrap itself around the stick. Similarly when a wire moves across a magnetic field the lines of force will wrap themselves around the wire. That is, a potential difference will be created at the extremities of the wire. This particular method of inducing a current is one modification of a general principle announced by Faraday in 1831. This principle may be stated as follows: When the number of lines of force passing through a closed coil of wire is changed, a current of electricity is set up in that wire. This

change may be effected in any manner whatever. The direction of the lines of force may be reversed (thus diminishing the number of lines to zero and increasing to a negative value); the coil may be moved across a field which is not uniform, or it may be rotated around one of its diameters as an axis in a uniform field. In any case a current of electricity will be generated. The only question with which we need to concern ourselves is: "Has the number of lines of force enclosed by the coil been changed?" If this number of lines has been changed, a current has been set up. If the number of lines has not been changed, there has been no current set up. Let us consider the case of a coil of wire which is not closed. We know that the current flowing in a wire is equal to the potential difference divided by the resistance. By opening the circuit of the coil, the resistance is made infinite and the current therefore reduced to zero. But there is a potential difference at the terminals of the coil, and upon completing the circuit a current will flow. Therefore we may say that when the number of lines passing through a coil is changed, a potential difference is established between the ends of the coil, and if these ends be connected a current of electricity will flow.

The most convenient method of changing the number of lines of force passing through a coil is either to reverse the direction of the lines of force, as in a transformer, or to rotate the coil around an axis which is

## 24 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

perpendicular to the lines of force, as is done in a dynamo.

The potential difference generated is proportional, not to the number of lines of force included by the coil, but to the rate of change of the lines. If a single rectangular turn of wire, as shown in Fig. 3, is rotated

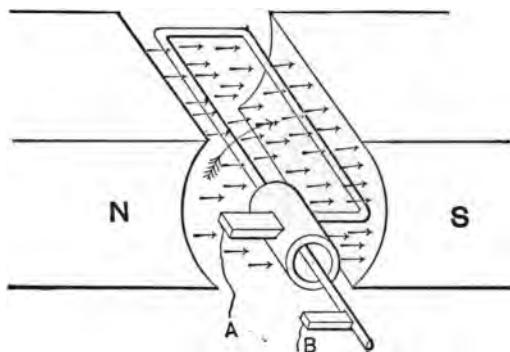


FIG. 3.

between two magnet poles, *N* and *S*, and around one of its sides as an axis, the combination may be considered as a dynamo of the most elementary form. A brush of copper resting against the side considered as a centre provides means of making electrical connection with this end of the coil, while a second brush resting on a copper tube to which the other end of the coil is connected makes contact with *this* end. Consider the coil in a horizontal position as shown in Fig. 3. In this position it lies parallel to the lines of force

and includes none. The instant it turns from the parallel position the lines begin to thread through the coil. This rate of change in the number included (from zero to a finite quantity) is evidently greater than at any other part of the half-revolution, for at any other time the rate of change is the difference between two finite quantities. As the revolution progresses the number of lines included gradually increases, the rate of cutting diminishing in a corresponding degree, until the coil has moved through an angle of  $90^\circ$  and is perpendicular to the lines of force. At this instant it is clear that a maximum number of lines of force will be included by the coil. But when the coil is perpendicular to the lines of force its motion is parallel to the lines, and the rate of cutting lines is zero. Therefore, when a maximum number of lines is included by the coil the induced potential difference is a minimum, and when a minimum number of lines is included a maximum potential difference is generated. As the coil advances the number of lines diminishes, until at  $180^\circ$  they become zero. After this they increase to a maximum at  $270^\circ$  and diminish again to zero at  $360^\circ$ , a complete revolution. Thus in one revolution the potential difference has twice become a maximum and twice reduced to zero.

Having determined the comparative numerical values of the potential differences, the next step is to

find their direction. If the two ends of the coil are connected through a resistance, a current of electricity will flow from the side of higher potential to the one of lower. The side of high potential is called the positive side and is indicated by the sign  $+$ ; while the side of low potential is known as the negative side and is indicated by the sign  $-$ .

There are many rules given in the text-books for determining the direction of the induced current. Probably the most satisfactory of them is the following:

Place the right hand in the position shown in Fig. 4, with the thumb, forefinger, and middle finger at right angles to each other. Then let the forefinger point in the direction of the lines of force, and the thumb in the direction of the motion. Then the middle finger will indicate the direction of the induced current.\* The following association of the finger with the function it represents has been pointed out:

FORefinger = lines of FORce ;  
 thuMb = Motion ;  
 mIddlefinger = Induced current.

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\* If the left hand be used for a motor and the forefinger point in direction of the lines of force and the middle finger in the direction of the current flowing in the wire, the thumb will indicate the direction of the motion. We have then to remember that the RIGHT *must be used for a DYNAMO* and the LEFT hand for a MOTOR.

Applying this rule to the combination shown in Fig. 3, we note the following characteristics:

In the position shown the current would flow from brush *A* to brush *B*; that is, *A* is + and *B* is -. When the coil has moved through  $90^\circ$ , we have seen

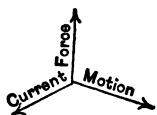
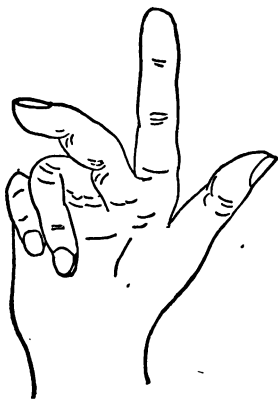


FIG. 4.

that the potential difference is zero. At  $180^\circ$  *A* is - and *B* is +. At  $270^\circ$  the potential difference is again zero, and at  $360^\circ$  *A* is + and *B* is - as in the beginning. Examining the action with this new light, we find that the potential difference is a maximum in the position shown in Fig. 3, that it gradually diminishes to

zero at  $90^\circ$ , attains a negative maximum at  $180^\circ$ , is again zero at  $270^\circ$ , and reaches the starting point, a positive maximum, at the end of the revolution. As will be shown in a subsequent part of this work, the potential difference at any time is proportional to the sine of the angle through which the coil has advanced.

If the two brushes *A* and *B* were connected by a resistance, when the coil is in the position shown, a maximum current will flow from *A* to *B*. This current will gradually decrease to zero at  $90^\circ$ . After passing this point the current will flow from *B* to *A* and increase to a maximum at  $180^\circ$  and diminish to zero again at  $270^\circ$ . Then the current will flow from *A* to *B*, and increase to a maximum at  $360^\circ$ . Thus for one half the revolution a current flows from *A* to *B*, and for the other half from *B* to *A*, and this current is not steady, increasing from zero to a maximum and diminishing again to zero. Starting from the position where a maximum number of lines is included in the coil, the potential difference generated is zero, and continuing around the revolution the potential difference varies as shown in the curve, Fig. 5, where the angles through which the coil has advanced are plotted as abscissæ, and the potential difference generated as ordinates.

The field for a current of this description is very limited, and it will be necessary, first, to cause the current to flow always in the same direction from brush to

brush, and, second, to transform it from an uneven, pulsating current to one that will be approximately even. Let us return to the rectangle of wire shown in Fig. 3. Instead of revolving the rectangle around one of its sides as an axis we might have revolved it around an axis parallel to and midway between the two sides.

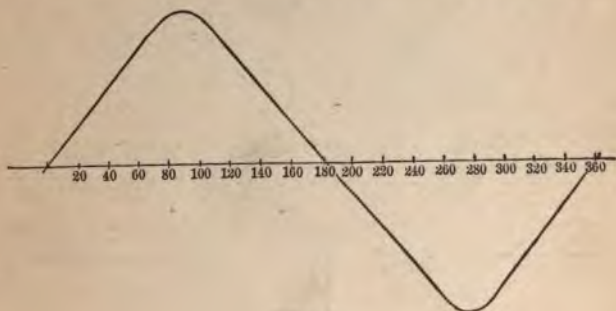


FIG. 5.

Under these circumstances the number of lines included by the coil will have remained the same, and it is evident that they will be reversed the same number of times in one revolution. We have now the same conditions as at first in regard to the generation of a current, except that the wire is cutting across the field at one half its former speed. On the other hand, the side of the rectangle originally used as an axis is now cutting lines, whereas in the first case it was idle. Therefore, though the speed has been diminished one half, the potential remains the same, since the length

of active wire has been doubled. It will be shown later that the important point to consider in regard to the loop is its area and not its form. Let us make another change in the loop as shown in Fig. 3. Suppose the tube in that figure be split longitudinally into two equal parts,  $m$  and  $n$ , and let one part be connected to each of the two ends of the turn of wire. Then letting a brush rest upon each of the sections of the tube, we have the arrangement shown in Fig. 6. This arrangement, though similar to the one shown in Fig. 3, will cause a very different current to flow between the brushes  $A$  and  $B$ . Just before attaining

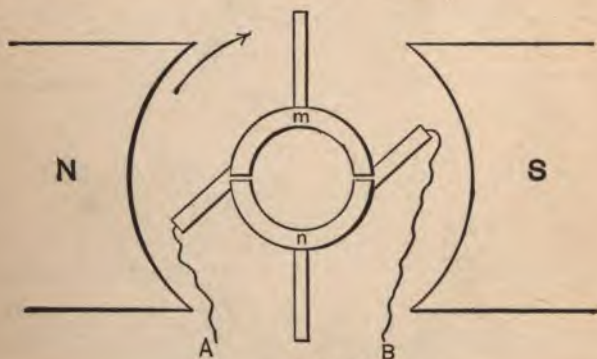


FIG. 6.

the vertical position shown, the current is flowing from brush  $B$  to brush  $A$ . When the coil is in a vertical position there is no potential difference, and the brushes rest on both sections  $m$  and  $n$  of the

split tube. At the next instant, when the coil begins again to cut lines of force, the section  $n$  passes from under brush  $B$ , and section  $m$  passes from under brush  $A$ . Therefore brush  $B$  rests only on section  $m$ , and brush  $A$  rests only on section  $n$  (Fig. 7). In this manner

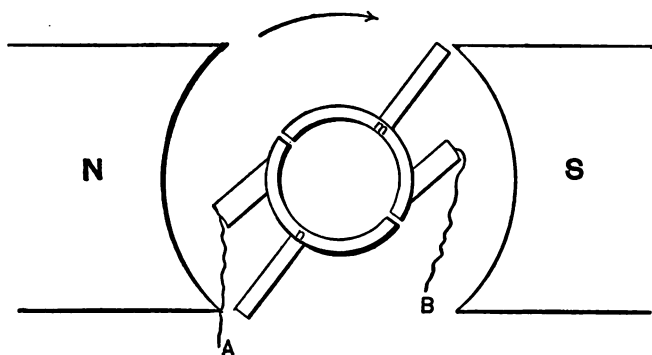


FIG. 7.

$B$  has the same potential as  $m$ , and  $A$  the same as  $n$ , until the coil has advanced through an angle of  $180^\circ$ . At this moment there is no potential difference, and the brushes rest upon both sections. The next instant the coil begins to generate current in the opposite direction, and as  $m$  was positive before, it is now negative. But as the split tube (or commutator) revolves with the coil, the section  $m$  has passed from under brush  $B$  and makes contact only with brush  $A$ , while section  $n$  is in contact with brush  $B$  (Fig. 8). Therefore, although the current in the coil has been reversed, still

## 32 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

the current between the brushes, on account of the commutator, still flows in the same direction. The

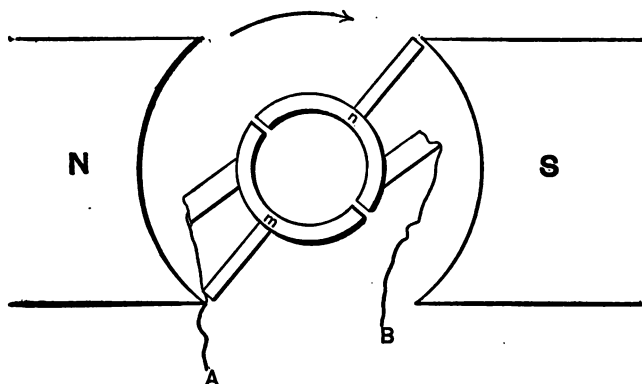


FIG. 8.

curve shown in Fig. 5 is still true for the coil, but on an investigation of the potential between the brushes we find the characteristics expressed by a curve similar to Fig. 9.

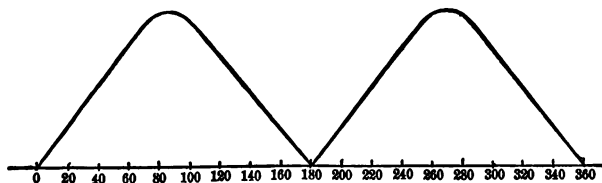


FIG. 9.

We have therefore advanced a step toward the solution of the problem, for now, while the potential dif-

ference fluctuates between zero and a maximum, its direction is constant. The final step is to reduce the amount of fluctuation until the current is approximately the same throughout the revolution.

If a second coil is added and the commutator split into four sections, Fig. 10, the conditions will be somewhat changed. Each coil will come into action when it comes within  $45^\circ$  of its position of maximum effect and will go out of action when it has passed  $45^\circ$  beyond that point. Consider the potential between the

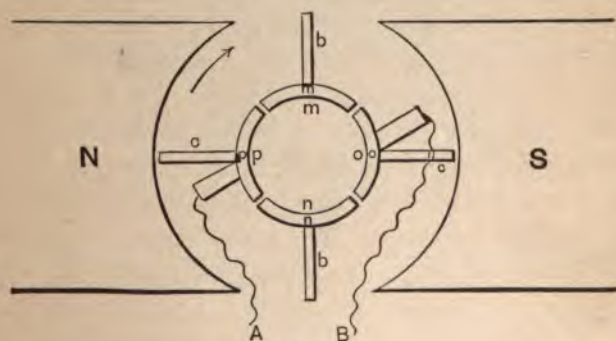


Fig. 10.

brushes, Fig. 10, during one revolution. The coil is in a maximum position and section *o* is positive and section *p* negative. The current will therefore flow from brush *B* to brush *A*. The potential will diminish until the coil has passed through  $45^\circ$ . Then the sections *o* and *p* of the commutator, and the coil, will

no longer be in connection with the brushes and may be neglected for the next quarter of a revolution. When the segments *o* and *p* pass from under the brushes the segments *m* and *n*, connected to coil *b b*, immediately replace them. Coil *b* is approaching its position of maximum effect, and therefore its potential difference is increasing. *M* is positive and the potential difference between the brushes is increasing and will increase for  $45^\circ$ , after which it will diminish for the next  $45^\circ$ . Then coil *b* goes out of action and *c* comes in again. While this action has been going on in coil *b* the potential difference of coil *c* has reduced to zero and is increasing again, but in the opposite direction. That is, *p* is positive and *o* is negative. Brush *B* is resting on segment *p* and is therefore still positive and the potential will increase for the next  $45^\circ$ . We have now completed half a revolution and the other half is a repetition of the action. We have seen that the potential is never lower than that generated at an angle of  $45^\circ$  from the position of maximum effect. For at an angle of  $45^\circ$  one coil is receding from its position of maximum effect and its sections of the commutator slip out from under the brushes, while the second coil is approaching the position and its sections come into contact. This result may be plotted as a curve, Fig. 11. In this curve the solid line represents the potential of the brushes or the potential generated by the coils while in contact with the brushes (which is the avail-

able potential difference), and the broken line is the potential difference generated by the coils while not

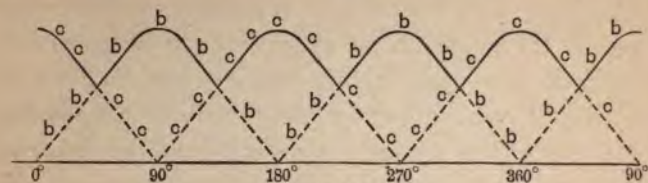


FIG. 11.

in contact with the brushes, and which need not be considered, as it in no way contributes to the potential difference of the machine. Each curve is marked by the letter of the coil which generated it. It will be noticed that when one coil is at a maximum the other is a minimum, which would be expected, as the coils are at right angles to each other. The difference between maximum and minimum potential in this



FIG. 12.

curve is very much less than in the curve shown in Fig. 9. If instead of four coils  $90^\circ$  apart we had used

### 36 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

eight coils  $45^{\circ}$  apart, the difference would have been even less, as is shown in Fig. 12. In this case each coil would be in operation for one-quarter of a revolution only. Thus by increasing the number of coils the flow of current can be made as steady as may be desired. Having now obtained a steady flow of current always in the same direction, let us consider briefly the construction of different types of dynamos.

## CHAPTER III.

### CLASSIFICATION OF MACHINES AND GENERAL PRINCIPLES OF THE MAGNETIC CIRCUIT.

THE elementary form of dynamo considered in the preceding chapter is a purely theoretical form and of no practical use except in demonstrating the general principles of current-induction.

The commercial dynamo operates under the same general laws and principles, but its form is very much modified.

It has been observed that iron is a much better conductor of lines of force than air. So great is its superiority that it will conduct several hundred times as many lines of force as air will carry under similar circumstances.

It will therefore be desirable to fill the space between the poles (Fig. 10) with iron rather than air. Obviously the most rational scheme for filling the space with iron is to wind the turn of wire upon an iron cylinder as shown in Fig. 13. The iron core and

### 38 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

the coils taken together are known as the armature. With a few exceptions all the armatures of continuous-current dynamos may be divided into two classes according to their cores, and into two other classes according to the connections of their coils. The two classes of cores are, the drum armature of Siemens

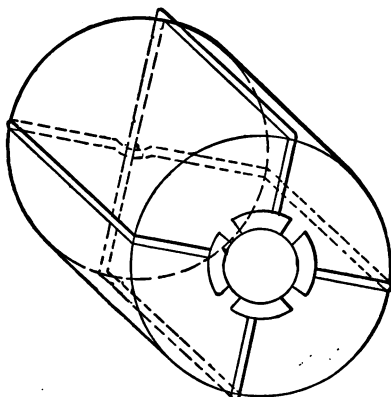


FIG. 13.

and the ring armature of Gramme. Figs. 13 and 14 show an armature of each class.

If these armatures are placed in magnetic fields, as in Figs. 15 and 16, there will be some little difference in the distribution of the magnetism. In each case the lines of force will confine themselves almost entirely to the iron, and consequently the length of the magnetic circuit will be a little greater in a Gramme

armature than in a Siemens. Then, too, the diameter of the ring armature is somewhat greater than that of the drum, for, on account of cutting out the centre of the ring, it is necessary to make the diameter greater in order to obtain a passage of sufficient cross-section

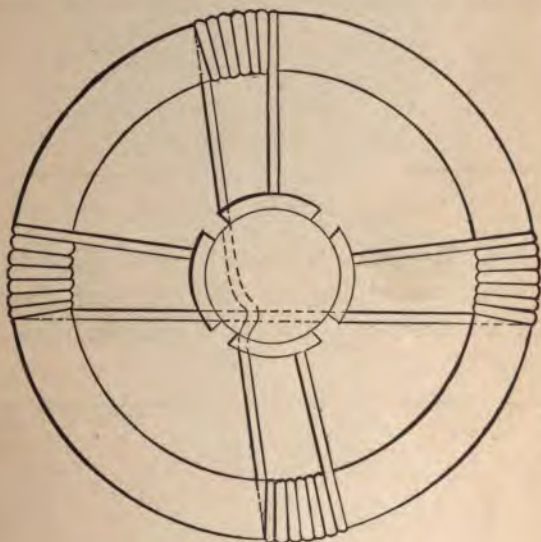


FIG. 14.

for the lines of force. A very important feature of the Gramme armature is that the windings do not cross each other and, besides being more easily repaired (since any coil can be removed without disturbing any other one), it is not so liable to break down when generating a high potential difference. For in the Sie-

#### 40 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

mens armature the full potential of the machine may be between two coils which cross each other, while in the Gramme the maximum difference of potential be-

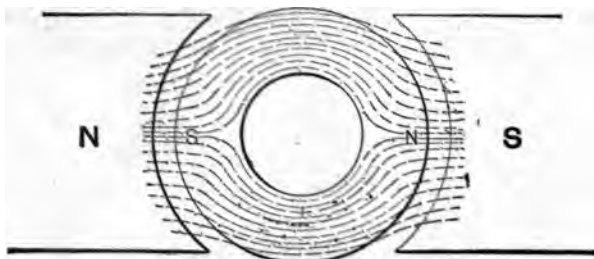


FIG. 15.

tween two adjacent coils is much lower. The division of armatures according to their winding gives two classes, the open-coil armature and the closed-coil armature.

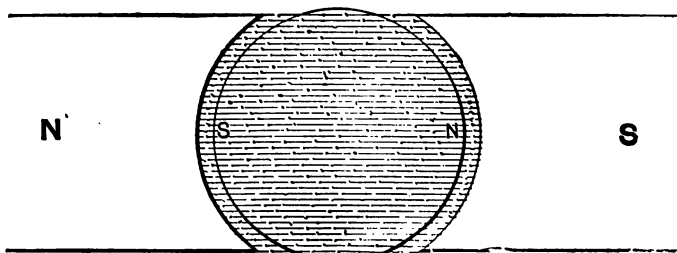


FIG. 16.

Turning back to Fig. 10, page 33, we notice that after the armature has passed  $45^\circ$  from the position shown, coil *c* is not in circuit with the line and does not

come in again until the coil has advanced through another  $90^\circ$ . During this time the circuit of coil *c* is open. This, then, is an open-coil armature. Figs. 13 14 show open-coil armatures of both the Siemens and and Gramme types. If, instead of having connected the coil so that it was out of circuit except when generating a certain potential, we had connected it so that it would be always in circuit (except when generating no potential at all, the moment of reversal, when it would

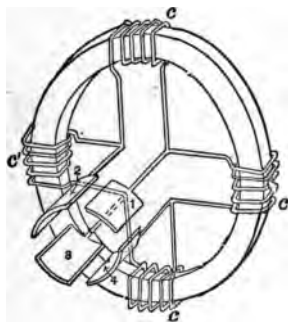


FIG. 17.

be short-circuited by the brush), we would have taken advantage of the small potential difference generated when the coil is not in position of maximum effect. This effect, though small, would increase the total potential difference. The connections in this case are as shown in Fig. 17 for a Gramme armature and in Fig. 18 for a Siemens. Fig. 17 should be carefully compared with

Fig. 14, and Fig. 18 with Fig. 13, to make clear the difference between a closed- and an open-coil armature.

It will be noticed in Fig. 17 (and also in Fig. 18) that all the armature coils are in series, forming a closed coil. It is therefore evident that the brushes divide the coils in halves and each half contributes to the potential between the brushes. A careful consideration will show that each half generates the full potential difference of the machine. The two halves

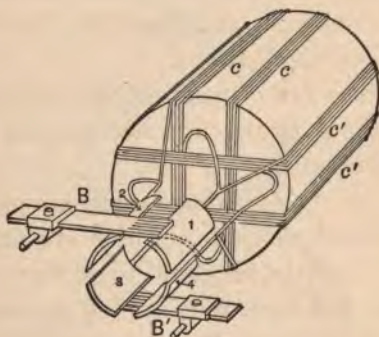


FIG. 18.

are connected in parallel. The electromotive force being the same for the whole armature as for one half, it might appear that there is not a great deal of advantage gained by using the two halves. It should be remembered, however, that the total resistance from brush to brush is one half of the resistance of one side and one quarter the resistance of all the armature coils in

series. Therefore while there is no gain in potential difference the resistance of the armature has been reduced. Then, too, the total armature current is equally divided between the two halves, and if the same size wire be used the current capacity of the armature is doubled. A moment's reflection will show that the second half is absolutely necessary, as the point of division is constantly shifting around the armature, and consequently if only one half were used the potential of the brushes would vary from zero to a maximum, and fluctuation would not be gradual but spasmodic.

We have thus far considered the magnetic field of  $N$  and  $S$  without taking into account the manner in which it was created.

Dynamos may be considered under three main heads according to their magnets. The first is the magneto machine, in which the magnets  $N$  and  $S$  are permanent. The second is the separately excited dynamo in which case the field-magnets  $N$  and  $S$  are electro-magnets, power for their excitation being derived from an external source.

The third, and only one which we will consider, is the self-excited dynamo, in which the fields are excited by the whole or part of the armature current.

It has been shown in Chapter I that when a current of electricity flows in a wire, lines of force are

created around the wire, and that the direction of these lines is controlled by the direction of the current.

If an observer is looking at the end of a wire carrying a current, and the lines of force around the wire are in the direction of the hands of a watch, the current is flowing *from* the observer. If in the *opposite* direction, the flow is *toward* the observer. There is a similar law for the polarity of electro-magnets. If a person is looking at the end of a helix of wire carrying a current of electricity, and *the flow of current* is in the direction of the hands of a watch, the observer is facing a south pole. If the flow of current is in the opposite direction, he is facing a north pole. Therefore in exciting the magnets by a coil of wire it is necessary to have the current in the coil flowing in the proper direction. With this brief digression let us return to the subject of classification of machines.

Self-excited dynamos may be subdivided into the series dynamo, the shunt dynamo, and the compound dynamo. In the series dynamo, Fig. 19, the whole current of the machine flows around the field-magnets. They are used almost entirely for constant-current work. The shunt dynamo, Fig. 20, is the one generally used for small powers at constant potential.

In the shunt machine the field is excited by very many turns of fine wire connected in shunt across the line. The current in the field or shunt circuit is

very low, not over a few per cent of the total armature current. The potential is, however, the full potential of the dynamo. In the series dynamo the fall of potential over the fields is very low, but the current is the full current of the machine. For dynamos of large capacity when designed for constant potential the

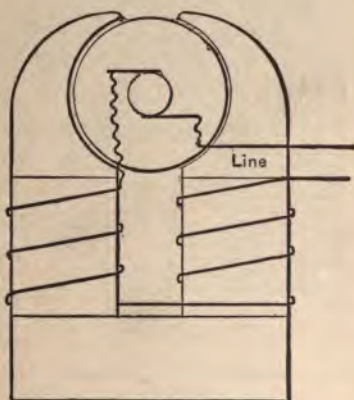


FIG. 19.

simple shunt dynamo is not satisfactory. It is noticed that as the load increases the potential drops. To avoid this, the compound dynamo, Fig. 21 is used. In this machine the field is excited by a shunt circuit as in the simple shunt dynamo, with the exception that a few turns of wire, in series with the line, are also wound around the magnets. When the current in the line increases, the increase of current in these

## 46 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

series coils compensates for the tendency of the potential difference to drop.

If the number of turns in series with the line is great enough, the potential will rise instead of drop. In this case the dynamo is said to be overcompounded.

In place of classifying fields by their winding they

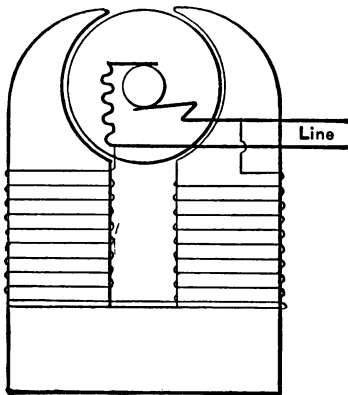


FIG. 20.

could have been divided according to their magnetic circuits. Figs. 19, 20, and 21 are all of the class known as single magnetic circuit, because the flow of magnetism is as in a single circuit. This is not, however, the only kind of circuit in use. Fig. 22 shows a dynamo having a double magnetic circuit. This type of machine is sometimes called a consequent pole machine. Broadly speaking, neither can be said to excel the other. The requirements are different in different

cases, and while one type of field may have a decided advantage in some particular instance, it is counterbal-

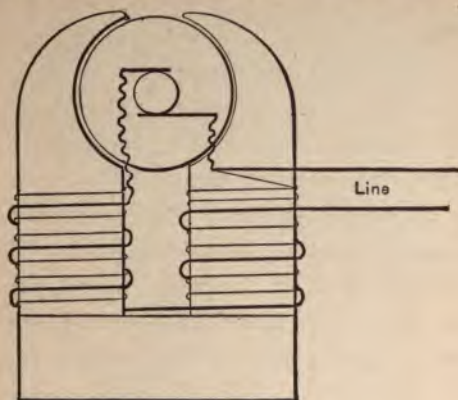


FIG. 21.

anced by the evident superiority of the other in some other branch. It is equally true of armatures that one

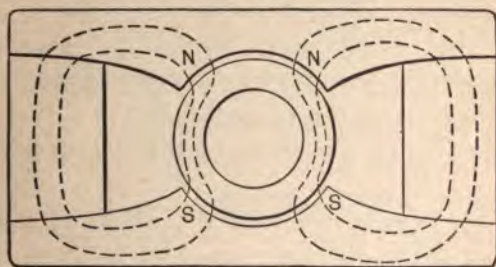


FIG. 22.

form is not best for all purposes. It is therefore necessary to caution the student not to become too firmly

prejudiced in favor of any particular form of construction, but to consider the advantages of each type in relation to the problem before him at the time. Particular problems require particular solutions, and that which is best adapted for use under one set of conditions may be of no service at all under different circumstances.

Multipolar fields require no special treatment. They may be considered as composed of a number of two pole fields joined together. It is a popular opinion with some people that an armature having the same number of turns will, at the same speed, generate a potential twice as great in a four-pole as in a two-pole field. This is an error, as will be shown in a subsequent part of this work. If the total turns on the armature are the same, and the magnetic field of the same intensity, the two machines will at the same speed generate the same electromotive force. Each conductor in the four-pole machine will generate twice the potential difference generated by a similar conductor in the two-pole machine, but a necessary change in the grouping of the coils makes the potential difference between the brushes of the two machines the same.

But little benefit would be derived from a general discussion of the different forms of field magnets at this stage. The idea is rather to think of the field as causing lines of force to circulate around the magnetic circuit. This is its only function—to create a mag-

netic flow—and it is evident that it can assume many forms.

Before leaving this subject it will be necessary to study the effect of a current flowing in the armature.

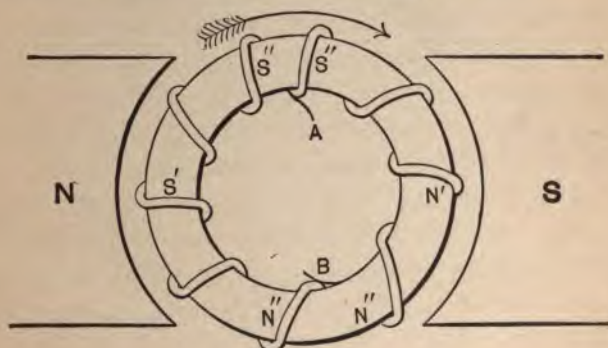


FIG. 23.

We have seen, Figs. 15 and 16, how the lines of force due to the magnets *N* and *S* are distributed. There is also a magnetic force due to the armature itself. Consider the case of a ring armature as shown in Fig. 23. The current leaves the armature by a brush at *A* and enters by a brush at *B*.

The current in the armature has magnetised the core with a *N.* pole at *B* and a *S.* pole at *A*. These poles are *N'' N''* and *S'' S''*. But there are the two poles *N'* and *S'* in the armature due to the magnets *N* and *S*. The result will be that the poles will shift and the distribution of the lines of force will be

similar to Fig. 24. The amount of shifting will depend on the relative strengths of the poles. That is, if  $N$  and  $S$  be constant the shifting will be greater as  $N''$  and  $S''$ , or the armature current, increases.

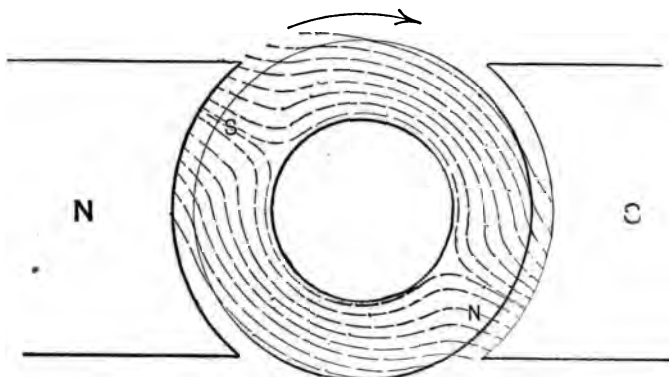


FIG. 24

An immediate effect of this shifting of the poles is that the part of a revolution where a coil is including a maximum number of lines is shifted in a corresponding degree. It is evident that the coil is including the maximum number of lines when it is perpendicular to the lines of force. The diameter of the armature marked by the plane of a coil when it is being commuted is called the diameter of commutation. Therefore the position of the brushes must be changed to correspond, for if a coil is commuted at any other time than when its potential is practically zero a violent sparking will ensue.

The cause of this sparking is not far to seek. When the current in a closed-coil armature is commuted the coil is for the moment short-circuited by the brush, and unless this occurs at a time when the coil is cutting very few lines there will result in the coil a heavy current, and when that segment of the commutator passes from under the brush there will be a violent spark. The shifting of the brushes referred to is known as changing the lead, and it is evident that the lead given the brushes must be increased as the current in the armature becomes greater. If the strength of  $N$  and  $S$  be very great as compared to the magnetism generated by the armature, the change of lead will not be so marked as otherwise.

## CHAPTER IV.

### THE DYNAMO AS A MOTOR.

THE preceding pages have considered the dynamo as a generator of electricity. It has been shown that when a coil of wire is rotated in a magnetic field, a current of electricity is set up in the wire. It has been shown *how* a current of electricity is generated by rotating an armature in a magnetic field. It will now be shown that this action is reversible. If a current of electricity is passed through an armature free to revolve and situated in a magnetic field, then rotation will result. In order to fully understand this phenomenon it is necessary to study one characteristic of lines of force which we have not yet considered. This is their property of shortening themselves. The lines must be considered as possessing a certain amount of elasticity. They may be stretched along path, but they will always have a tendency to contract and take the shortest path between the two

points. Consider the combination of magnets shown in Fig. 25, where the magnets are immovable. Then a line of force, as shown in the sketch, will tend to shorten itself into a horizontal line and there will be a force acting at each end of the small magnet tending to turn it into a horizontal position. Now conceive this small magnet to be very short and stout, and then re-

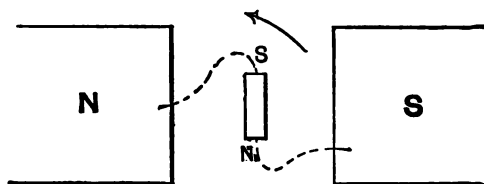


FIG. 25.

place it by a wire carrying a current of electricity of which it is the equivalent magnetic shell. This wire or coil will evidently lie in a horizontal plane, and the tendency of the line of force to shorten itself will (if the coil be free to rotate) turn it toward a vertical position. As it approaches this position the force will gradually diminish. If the coil is replaced by an armature provided with a commutator, another coil will come into action when the armature has turned through a certain angle and (in the case of an open-coil armature) the coil which has passed the position of maximum effect will be cut out of the circuit. The result will be a continuous rotation of the armature.

## 54 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

Fig. 26 represents the small magnet of Fig. 25 replaced by a turn of wire carrying a current. If the

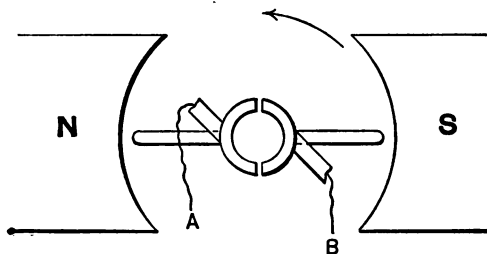


FIG. 26.

polarity of this coil is to be the same as that of the small magnet of Fig. 25, it is evident that the current must enter at brush *A* (see page 44) and leave at brush *B*. Since the coil replaces the magnet in Fig. 25, it is evident that rotation in the two cases will be in the same direction, and this direction is indicated by the arrow. This could have been determined from the rule given on page 26, remembering to use the left hand as pointed out in the footnote. But we have seen that when an armature rotates in a magnetic field an electromotive force is set up in the armature.

If a coil is rotated in a magnetic field in the direction indicated by the arrow in Fig. 26, there will be a current set up in the wire, and the flow of current will be from brush *A* to brush *B* outside the machine and

from brush *B* to brush *A* inside. But we have seen that the current which causes rotation flows from brush *A* to brush *B* in the machine, and consequently the two currents will oppose each other. That is, when a motor is running it develops an electromotive force which opposes the flow of current and may be termed a counter-electromotive force. The effective electromotive force is therefore the difference of the impressed and counter-electromotive forces. The effect of the counter-electromotive force is the same as increasing the resistance of the armature.

The counter-electromotive force of a motor is one of its most important characteristics, as will be fully shown in the subsequent portions of this work. It is the one thing necessary for success, and those inventors who are trying to build motors without counter-electromotive force are not only striving for an impossibility, but for that which, if it could be attained, would destroy the usefulness of their machines.

The motor being neither more nor less than a dynamo, it is not necessary to give a classification of the different types. The series, shunt, and compound motors are the same as the dynamos of the same class and may be so classified. They may be classified according to their fields in the same way that dynamos are divided, or if preferred according to their type of armature. The classification in most common use, however, is based upon the connections, dividing them

into series, shunt, and compound machines. That this is the more important feature will be more fully understood at a later time. For the present it is sufficient to say that their action, regulation, etc., are governed, not by the shape of the armature or of the fields, but by their connections. A series motor will give similar results under the same conditions no matter whether the armature is of the Siemens or the Gramme pattern. The same is true of a shunt motor. Almost any change can be made in the machine provided the connections remain unaltered. But if a change is made from series to shunt or *vice versa*, entirely different results are obtained.

We have seen that the current in the armature of a dynamo distorts the magnetic field, and it is but reasonable to expect a similar distortion in the case of a motor. Turning back to Fig. 23, page 49, if the combination is to be considered as a motor the current must enter the armature at brush *A* and leave it at brush *B* in order that rotation may be in the direction indicated by the arrow. This current will tend to magnetize the core with a north pole at *S''* and a south pole at *N''*, the reverse of the tendency in a dynamo. Consequently the actual pole will be shifted to the right and not to the left, and the field will be as shown in Fig. 27.

In a dynamo the lines seem to be dragged around by the armature (Fig. 24), while in a motor they seem

to crowd up toward the part of the pole where the wires of the armature enter the field, as shown in Fig. 27. An important effect of this difference is that in a dynamo the brushes were given a forward lead (in the direction of rotation), while in a motor a backward lead must be given to avoid sparking. In each case the angle of lead is increased with the load, so that with a dynamo the brushes must be shifted forward as the load increases, and backward in case of a motor.



FIG. 27.

Figs. 27 and 24 should be carefully compared. Generally speaking, the principle of the dynamo is the same as that of the motor, and what is true in one case will hold in the other. One point, however, should not be overlooked. A series machine when operating as a motor will run against the brushes, while a shunt machine rotates in the same direction,

whether used as a dynamo or a motor. With a compound-wound motor the direction of rotation will be governed by the predominating coil. The direction of rotation depends, not upon the absolute polarity of either the armature or field, but upon their polarity relative to each other. If the polarity of either is reversed without reversing the other, the direction of rotation is reversed. If the polarity of both armature and field is reversed, there is no resulting reversal in the direction of rotation. It is evident that the action of a dynamo is to resist rotation, and it would be expected that if the directions of the currents in field and armature are the same, that the machine as a motor will rotate in the opposite direction. This is true, and in a series motor the relative directions of the armature and field currents are the same as in a dynamo and rotation is against the brushes. Remembering that the current in the armature of a dynamo flows from the negative to the positive brush, it is evident that if the positive brush of the machine is connected to the positive side of the line the armature current will be reversed, while in a shunt dynamo the field current will still be in the same direction. We have therefore reversed the armature but not the fields, and consequently the direction of rotation is the same in a shunt motor as in a shunt dynamo. On the other hand, if the negative brush of the machine is connected to the positive side of the line the current in the

armature will be in the same direction as in a dynamo, but the polarity of the fields will be reversed. Consequently in this case also the rotation will be in the same direction in a motor and a dynamo.

Since the armature current in a motor depends upon the difference of the electromotive force of the line and the counter-electromotive force of the motor, it is evident that when the armature is standing still, there being no counter-electromotive force to oppose the current, that an enormous current would flow if the normal working potential difference existed at the brushes. It is therefore necessary to have a resistance in series with the armature when starting a motor on a constant potential circuit. This resistance takes the place of the effective resistance of the counter-electromotive force and must be gradually reduced to zero as the speed of the armature and consequently the counter-electromotive force increases. This is not necessary on a constant-current circuit, since the same current flows whether the machine is at a high or a low speed. The drop of potential over the armature depends upon its resistance and upon the counter-electromotive force, and therefore when the armature is at rest and no counter-electromotive force is being generated the drop is that due to the resistance alone and is not then nearly so great as when the armature is rotating.

Having now considered briefly the principles of the

## 60 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

dynamo and motor, which are in general identical, and indicated the main difference in minor points, we will proceed to a consideration of the laws governing the economic design of these machines.

## CHAPTER V.

### CALCULATIONS PERTAINING TO THE MAGNETIC CIRCUIT.

IN some respects the magnetic circuit may be considered as the most important part of a dynamo. It is the body of the machine upon which the wire is wound. A change in one part may necessitate a change in all the other parts which is often expensive. On the other hand, the expense of rewinding may be comparatively small.

Therefore the dimensions of the magnetic circuit should be carefully considered in order to avoid an expensive alteration after the machine is completed.

The following symbols will be used in the subsequent chapters, and so far as possible in their present significations. When this rule is departed from, the meaning of the symbol will be given in the text.

#### TABLE OF SYMBOLS.

$a$  = density of lines of force.

$b$  = diameter of armature core.

$c$  = current.

## 62 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

$C$  = number of conductors counted all around the armature.

$C_a$  = armature current.

$C_f$  = field current.

$d$  = length of a portion of the magnetic circuit.

$E$  = potential difference.

$E_1$  = hysteresis loss in ergs per cubic centimeter per cycle.

$e$  = length of arc on pole-piece.

$F$  = friction.

$g$  = hysteresis loss in ergs per revolution.

$h$  = number of turns in series coil.

$k$  = radius of armature.

$K$  = a constant.

$l$  = length of armature parallel to shaft.

$m$  = " " an average line of force in the armature.

$M$  = length of an average line of force in the field.

$n$  = number of turns of wire.

$o$  = " " " in shunt coil.

$R$  = resistance.

$R_a$  = resistance of armature.

$R_e$  = " " series coils.

$R_f$  = " " field coils.

$S$  = area of a portion of the magnetic circuit.

$w$  = work performed by a motor.

$AB$  = cross-section of field.

$HP$  = horse-power.

$Z$  or  $\beta$  = total induction.

$\eta$  = commercial efficiency.

$\omega$  = angular velocity.

$\epsilon$  = counter-electromotive force.

$\nu$  = leakage coefficient.

As has been pointed out, the function of the field is to cause lines of force to pass through the armature. For this reason one of the first problems presenting itself is the determination of the induction through the armature from obtainable data. There are two well-known methods of making this calculation. One is due to Mr. Gisbert Kapp, the other to Drs. J. and E. Hopkinson. Kapp's method is practically as follows:

Consider a ring, Fig. 28, cut across on one side by

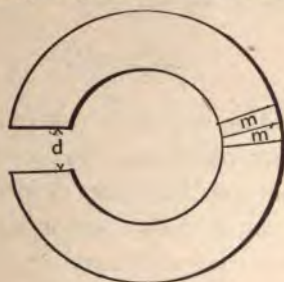


FIG. 28.

two planes the distance between which is  $d$ ; let this distance be very small.

If the area of the metal be  $S'$  and the density be  $\alpha$ , then the total lines of force flowing across the space

$d$  will be  $Sa$ . Now conceive the ring to be made up of a great many small magnets,  $m m'$ . Next consider each of these small magnets to be replaced by a turn of wire carrying a current of electricity. The magnetic moment of this series of magnets is  $ncS$ , where  $n$  is the number of turns of wire and  $c$  is the current flowing. This is evidently true, since (according to Ampere) each elementary magnet may be replaced by an equivalent magnetic shell the product of whose current and area is the magnetic moment of the elementary magnet. This series of elementary magnets having their poles in contact, the magnetic moment of the series is equal to the product of the distance between and the magnetism distributed over the end surfaces. We have, since the two expressions are for the same magnet,

$$Sad = ncS. \quad . \quad . \quad . \quad . \quad (1)$$

This would be the expression provided the effect is due to the current alone. But we have seen that from a unit magnetic pole  $4\pi$  lines of force emanate, and from a pole of strength  $Sa$  there must emanate  $4\pi Sa$  lines; and representing this number by  $Z$ ,

$$Z = 4\pi Sa,$$

or

$$Sa = \frac{Z}{4\pi}.$$

Substituting this value of  $Sa$  in equation (1),

$$Snc = \frac{Z}{4\pi}d,$$

$$Z = \frac{4\pi ncS}{d},$$

which may be written in the form

$$Z = \frac{4\pi nc}{\frac{d}{S}} \dots \dots \dots (2)$$

This equation has been derived for plane surfaces, but is also true with curved, provided  $d$  is small compared to  $S$ . This may now be applied to the dynamo. If  $l$  = length of the armature, and  $e$  = length of the arc on pole,  $S = le$ ; and writing  $P$  for exciting power,

$$Z = \frac{4\pi P}{\frac{2d}{le}}.$$

The factor 2 is introduced since there are two air gaps, one on each side of the armature.

This equation may also be written

$$Z = \frac{P}{\frac{2d}{4\pi el}} \dots \dots \dots (3)$$

This expression is very similar to Ohm's law, for  $P$  represents a magnetic pressure or magneto-motive

force, and  $\frac{2d}{4\pi el}$  may be considered as a magnetic resistance. Representing this by  $R$ , we may write

$$R = \frac{2d}{4\pi el}$$

Now the electrical resistance of a conductor is the product of the specific resistance of the metal multiplied by the length and divided by the cross-section. Similarly, magnetic resistance is made of length ( $2d$ ), cross-section ( $el$ ), and specific magnetic resistance, which must be  $\frac{1}{4\pi}$ . This value  $\frac{1}{4\pi}$  may be called the specific magnetic resistance of air.

Equation (3) gives the value of the flow in absolute or C. G. S. units. To reduce to what he considers more convenient units Mr. Kapp divides the lines of force by 6000,\* changes the lengths from centimeters to inches, and expresses  $P$  in ampere-turns. By this alteration equation (3) becomes

$$6000Z = \frac{\frac{P}{10}}{\frac{2.54}{6.45} \times \frac{2d}{4\pi el}} ;$$

$$Z = \frac{P}{1880 \frac{2d}{el}}$$

---

\* A Kapp line is equal to 6000 C. G. S. lines of force.

It must be remembered that this formula is correct only provided the iron in the coils does not contribute to the lines (which is by no means true), and that there is no resistance in the circuit except that of the air-

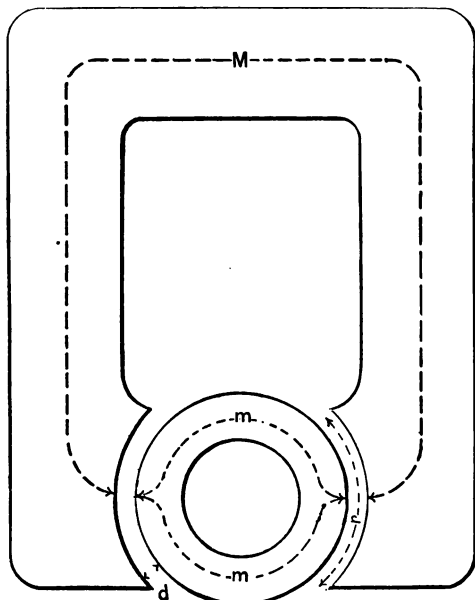


FIG. 29.

space. After a great many experiments Mr. Kapp gave the following value for the resistance of the air-space :

$$1440 \frac{2d}{el}$$

## 68 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

if the armature core and field magnets are of wrought-iron, and

$$1800 \frac{2d}{el}$$

if the armature core is of wrought-iron and the field magnets of cast-iron.

Further, he finds that the iron of the magnetic circuit offers some resistance; and taking the dimensions given in Fig. 29, he states the formula for the number of Kapp lines in the armature as

$$Z = \frac{P}{1440 \frac{2d}{el} + \frac{m}{ab} + \frac{2M}{AB}} \dots \dots (4)$$

if the armature core and field magnets are of well-annealed wrought-iron, and

$$Z = \frac{.8P}{1800 \frac{2d}{el} + \frac{m}{ab} + \frac{3M}{AB}} \dots \dots (5)$$

if the magnets are of cast-iron.

In these formulæ

$m$  = length of average line in armature;

$M$  = " " " " " field;

$ab$  = cross-section of armature;

$AB$  = " " field.

$P$  = ampere-turns.

$Z$  = Kapp lines.

The dimensions are in inches.

These values are for single magnetic circuits. If the dynamo has a double magnetic circuit as shown in

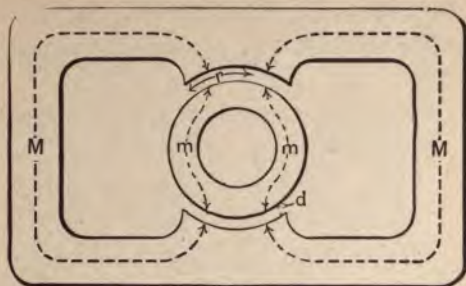


FIG. 30.

Fig. 30, the formulæ are somewhat modified.

Each side of the circuit contributes one half the number of lines, and for this case Mr. Kapp writes

$$\frac{Z}{2} = \frac{P}{1440 \frac{2d}{el} + \frac{2m}{ab} + \frac{2M}{AB}} \quad \dots (6)$$

for wrought-iron magnets, and

$$\frac{Z}{2} = \frac{.8P}{1800 \frac{2d}{el} + \frac{2m}{ab} + \frac{3M}{AB}} \quad \dots (7)$$

if the magnets are of cast-iron.

These formulæ apply to fields where the intensity of magnetization does not exceed 10 Kapp lines. For more intense fields the magnetizing power required is considerably greater than that given by the equation,

The second method is due to Drs. J. and E. Hopkinson and is in some respects more satisfactory than Kapp's method. In order to fully appreciate this method it is necessary to first consider some problems in magnetism.

Conceive a closed curve drawn in a magnetic field. Consider this line to be composed of many small elements. Then the force required to move a free unit pole around this curve is equal to the sum of the lengths of these small elements each multiplied by the force at its centre estimated in the direction of the line. This sum is called the line integral of magnetic force along that line. The two cases of importance are: First, when the line lies wholly in the air and does not link or surround an electric current. In this case the line integral is evidently zero, for no energy is expended in moving the pole around the path. Second, when the line surrounds or is looped with a wire carrying an electric current.

Consider the simplest case: a straight wire carrying a current, the return being a great distance away. Consider a circular line at the distance  $r$  from the wire. The length of the line is evidently  $2\pi r$ , and the force at any point is  $\frac{2c}{r}$ . Then the line integral equals

$2\pi r \frac{2c}{r} = 4\pi c$ . Now consider that in place of a straight wire we have a solenoid of  $n$  turns, and that

the current is expressed in amperes rather than in C. G. S. units. Then

$$\text{line integral of magnetic force} = \frac{4\pi nc}{10}. \quad (8)$$

This is the general form of the equation and can be shown to be true in all cases. The term magneto-motive force has also been applied to this quantity.

Consider a long thin wire placed in a magnetic field parallel to the lines of force. If the length of the wire be represented by  $l$  and its cross-section by  $s$ , the number of lines of force which would pass through the wire when placed in a field of intensity  $H$  (due to the field alone) is  $Hs$ ; and if the wire be cut in the middle, this is the number of lines (due to the field alone) which would cross the gap. We have seen that from a pole of strength  $m$   $4\pi m$  lines of force emanate; and if the poles induced at the ends of this wire are of strength  $m$ , there will be  $4\pi m$  lines of force added to the  $Hs$  lines.

Representing by  $\beta$  the number of lines of force passing through every square centimeter of cross-section of the wire,

$$\beta s = Hs + 4\pi m;$$

$$\beta = H + 4\pi \frac{ml}{sl}.$$

But  $\frac{ml}{sl}$  is the moment of the magnet divided by its volume; and if this be represented by  $I$ ,

$$\beta = H + 4\pi I.$$

But  $I$  depends for its value on the strength of the field producing it; and if the ratio between  $I$  and the field is represented by  $K$ ,

$$I = KH$$

or

$$\begin{aligned}\beta &= H + 4\pi KH \\ &= H(1 + 4\pi K) \\ &= \mu H.\end{aligned}$$

This value  $\mu = 1 + 4\pi K$  is called the permeability of the iron and represents the ratio of induced magnetism to magnetizing power. It is evident that for air the value of this ratio is unity.

In a magnetic circuit we have seen that the magnetic resistance is similar to that offered by a conductor to a current of electricity; that this resistance was of the character of a length multiplied by a suitable factor (depending on the quality of the iron) and divided by an area.

This factor is the one just determined; and since

the resistance diminishes as the quality of the iron improves, we may write

$$R = \frac{d}{\mu S},$$

where  $d$  is the length of the magnetic circuit,  $S$  its area,  $R$  the magnetic resistance, and  $\mu$  the permeability of the iron.

If  $\beta$  represent the number of lines of force in the circuit, it is evident that to force these lines through the circuit it is necessary to have a magneto-motive force or line integral of magnetizing force equal to

$$\frac{d\beta}{\mu S},$$

and from equation (8) we may write

$$4\pi nc = \frac{d\beta}{\mu S}, \quad . . . . . (9)$$

which is the equation for the magnetizing power (in C. G. S. units) required.

In applying this formula to a dynamo it is desirable to alter it in some ways. In place of finding the magnetizing force required for the whole circuit, it is better to divide the circuit into several parts, to consider the parts separately and take the sum of the magnetizing forces as the value sought.

## 74 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

This is necessary, since the different portions of the magnetic circuit may not be of the same quality of iron and the value of  $\mu$  will not be the same throughout the circuit. Also, any one part may be considerably out of proportion and should be corrected. Therefore the formula gives not only a method of determining the ampere-turns required, but it also provides means of inspecting the proportions of the parts and of determining the effect of an alteration in any of them. The natural divisions of the magnetic circuit, Fig. 31, are

- Armature (1);
- Air-space (2);
- Pole-pieces (3);
- Field cores (4);
- Yoke (5).

Let  $d$  with subscripts 1, 2, 3, 4, and 5 represent the lengths of the average lines in these parts. Then

$$d = d_1 + 2d_2 + 2d_3 + 2d_4 + d_5.$$

Let  $S$  with similar subscripts represent the area of cross-section of the parts and  $\mu_1, \mu_2$ , etc., their permeabilities.

Assume that (by some miracle) all the lines of force which pass through the field cores also pass through the armature. This is by no means true, but the nature and extent of the error will be shown later.

From formula (9) the following values of the line integral for the parts are taken :

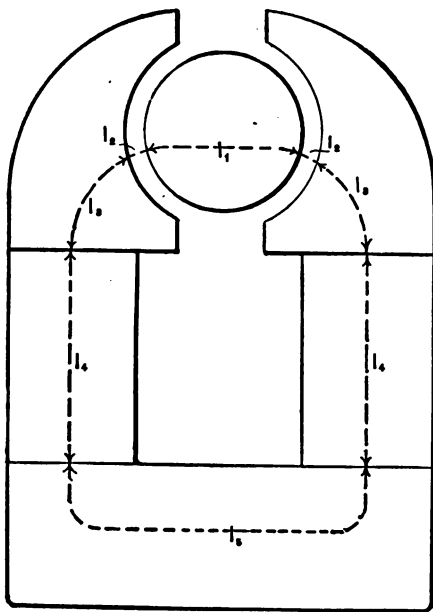


FIG. 31.

for the armature  $\frac{d_1 \beta}{S_1 \mu_1}$  ;

for the air-space  $\frac{2d_2 \beta}{S_2}$  ,

since the permeability of air is unity ;

$$\text{for the pole-pieces } \frac{2d_p\beta}{S_p\mu_p} ;$$

$$\text{for the field cores } \frac{2d_f\beta}{S_f\mu_f} ;$$

$$\text{for the yoke } \frac{d_y\beta}{S_y\mu_y} ;$$

and the total power required for the circuit is

$$4\pi nc = \frac{d_p\beta}{S_p\mu_p} + 2 \frac{d_f\beta}{S_f} + 2 \frac{d_p\beta}{S_p\mu_p} + 2 \frac{d_f\beta}{S_f\mu_f} + \frac{d_y\beta}{S_y\mu_y}. \quad (10)$$

In applying this equation to a dynamo it would be found that the ampere-turns given by the formula would be from 25 to 40 per cent too low. The reason of this error is quickly found.

We have assumed that all the lines of force in the field pass through the armature. This is by no means true, and to obtain a true formula it is necessary to find what per cent of the total lines is useful, that is, what per cent passes through the armature.

The ratio of the waste lines to the total lines is called the leakage of the machine, and is approximately constant for machines of the same type re-

gardless of size. The value of this ratio may be obtained as follows :\*

Where it can conveniently be done, disconnect one coil of the armature from the commutator and connect it to the terminals of a ballistic galvanometer. Where this is not convenient take several turns of very fine wire around the armature, placing it as near the core as possible, and connect the ends to a ballistic galvanometer. Turn the armature until the coil connected to the galvanometer includes all the lines passing through the armature. It is evident that when lines of force are passed through (or taken out of) this coil, a momentary current of electricity will flow through the galvanometer and a throw of the needle proportional to the disturbance will result. Therefore, if a current of electricity flowing through the field coils of the machine (the armature being disconnected so that no rotation will ensue) is broken, lines will be taken out of the coil on the armature (since the flow will reduce to zero) and a throw of the galvanometer will result. When the current is again allowed to flow around the coils there will be a similar throw in the opposite direction. If  $K$  is the constant of the ballistic and  $x$  the throw

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\* It has also been derived from purely theoretical considerations by Prof. Forbes, *Journal of Society of Telegraph Engineers and Electricians*, November 25, 1886.

## 78 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

of the needle, the number of lines of force passing through the coil of  $n$  turns on the armature is

$$\frac{Kx}{n}.$$

Now take a few turns of fine wire around the field-magnet and repeat the operations. If there are  $n'$  turns and the throw of the ballistic is  $y$ , the number of lines passing is

$$\frac{Ky}{n'}.$$

Then the ratio of useful lines in the armature to the lines in the field is

$$\frac{\frac{Kx}{n}}{\frac{Ky}{n_1}} = \frac{n'x}{ny}.$$

Since the value of  $K$  is eliminated, it is not necessary to determine it.

In a similar manner we may obtain the ratio of the lines in the armature to those in the poles,

$$\frac{n''x}{nz},$$

and for the yoke

$$\frac{n'''x}{nw}.$$

Representing the reciprocals of these values by  $\nu$  with suitable subscripts, we have

$$\frac{ny}{n'x} = \nu_4;$$

$$\frac{nz}{n''x} = \nu_3;$$

$$\frac{nw}{n'''x} = \nu_1.$$

When  $\beta$  lines of force pass through the armature, we have :

Through the pole-pieces.....	$\beta\nu_3$ .
“ “ field cores.....	$\beta\nu_4$ .
“ “ yoke.....	$\beta\nu_1$ .

Substituting these values in equation (19),

$$4\pi nc = \frac{d_1\beta}{S_1\mu} + 2\frac{d_2\beta}{S_2} + 2\frac{d_3\beta\nu_2}{S_3\mu_3} + 2\frac{d_4\beta\nu_4}{S_4\mu_4} + \frac{d_5\beta\nu_5}{S_5\mu_5}, \quad (11)$$

which is the correct value of the magnetizing force required to force  $\beta$  lines of force through the armature, neglecting the reactions of the armature itself.

Therefore the equation gives the magnetizing force required when the machine is running on open circuit.

Representing by  $x$  (with suitable subscripts) the magnetizing force applied to the different portions of the magnetic circuit, we may write

$$\begin{aligned}
\text{For the armature * } & \left\{ \begin{aligned} x_1 &= \frac{d_1 \beta_1}{S_1 \mu_1}; \\ \beta &= \frac{S_1}{d_1} \mu x_1. \end{aligned} \right. \\
\text{For the air-space † } & \left\{ \begin{aligned} x_2 &= 2 \frac{d}{S_2}; \\ \beta &= \frac{S_2}{2d_2} x_2. \end{aligned} \right. \\
\text{For the pole-pieces } & \left\{ \begin{aligned} x_3 &= \frac{2d_3 \beta_3}{S_3 \mu_3}; \\ \beta &= \frac{S_3}{2d_3 r_3} \mu_3 x_3. \end{aligned} \right. \\
\text{For the field coils } & \left\{ \begin{aligned} x_4 &= \frac{2d_4 \beta_4}{S_4 \mu_4}; \\ \beta &= \frac{S_4}{2d_4 r_4} \mu_4 x_4. \end{aligned} \right. \\
\text{For the yoke..... } & \left\{ \begin{aligned} x_5 &= \frac{d_5 \beta_5}{S_5 \mu_5}; \\ \beta &= \frac{S_5}{d_5 r_5} \mu_5 x_5. \end{aligned} \right.
\end{aligned}$$

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\* The value of  $d_1$  should be somewhat in excess of the shortest distance between the poles.

† The value of  $S_2$  should be about 13 per cent greater than the bored surface of the pole to allow for dissipation of the field.

Now give different values to  $x_1, x_2, x_3$ , etc., and calculate the corresponding values of  $\beta$ .

The formula for the air-space is evidently the equa-

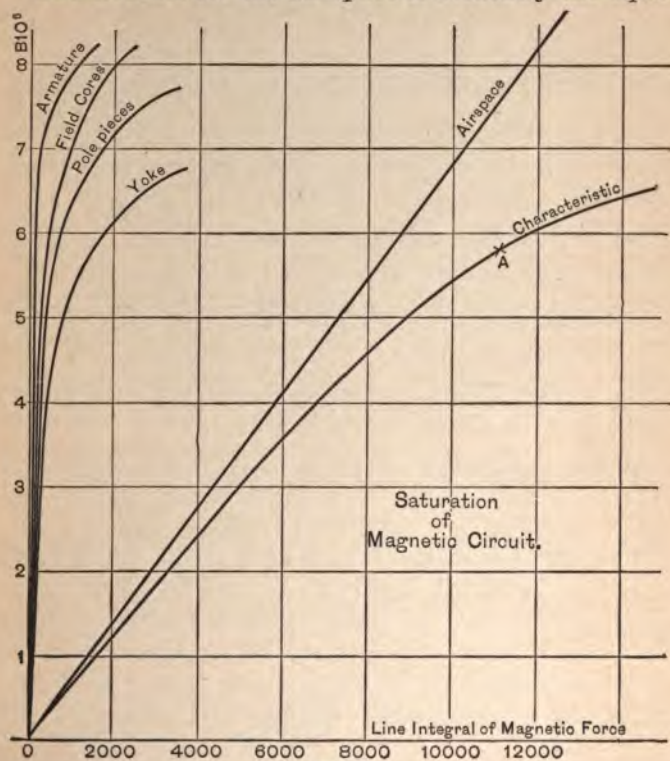


FIG. 32.

tion of a straight line passing through the origin. It is therefore necessary to determine only one point, preferably a point of rather high co-ordinates.

## 82 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

The other equations are all of similar form,

$$\beta = \frac{S}{d\nu} \mu x.$$

The value of  $\nu$  in the expression for the armature is evidently unity, and it has been shown how the value for the different parts of the circuit may be determined. It is now only necessary to determine the values of  $\mu$  in order that the values of  $\beta$  may be fixed for given values of  $x$ . These values may be taken from the curves (Appendix I). In taking these values it should be borne in mind that the values of  $H$  are per unit length, and that the assumed value of  $x$  must be divided by  $d_1$ ,  $d_2$ , etc., to determine the true value of  $H$ . This value must be determined for the different assumed values of  $x$ , and the corresponding value of  $\mu$  read directly from the curve for that class of iron.

For instance, if the length of the line through an armature is 12 cm. and the area of iron section 160 sq. cm.,

$$B = \frac{160}{12} \mu x,$$

and for a value 600 of  $x$  the value of  $\frac{x}{d}$  is 50. From the curve (Appendix I) for sheet-iron, we find the

corresponding value of  $\mu$  to be 290. Therefore when  $x = 600$ ,

$$B = \frac{160}{12} \times 600 \times 290 = 2,320,000.$$

Whenever it can be obtained it is of course desirable to have the  $H$  and  $\mu$  curve for the particular brand of iron used. In the absence of such information the curves given in the Appendix may be taken as fair average values.

Having found a number of values of  $\beta$  for the different portions of the magnetic circuit, curves should be plotted as shown in Fig. 32. The characteristic is for the machine as a whole, and the abscissæ for any ordinate may be found by adding together the abscissæ for the same ordinate in all the curves. This is the characteristic of the dynamo, and will be correct within a very few per cent.

By this method of plotting the curves for the parts separately it is an easy matter to determine the effect of any change in the dimensions. Perhaps a little more iron is needed in some one part and a little may be spared from some other. The economy of plotting these curves can hardly be overestimated.

## CHAPTER VI.

### THEORY OF WINDINGS, LOSSES, ETC.

HAVING determined the total induction through the armature, the next step is to calculate the potential difference developed by the armature. Consider first a

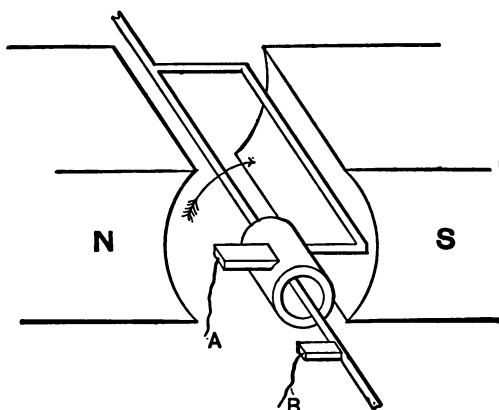


FIG. 33.

the armature of one turn, Fig. 33. *N* and *S* represent the two magnet poles, and *A* and *B* two brushes

which press against the ends of this single turn. Consider the field to be uniform, and let there be  $a$  lines of force passing through each square centimeter. Let the length of the coil parallel to the shaft be  $l$ , and let the dimension perpendicular to the shaft be  $k$ . Then the area of the coil is  $= lk$  sq. cm.

In one revolution the outside wire moves through  $2\pi k$  centimeters; and if  $r$  be the revolutions per minute, the speed of the wire in centimeters per second will be

$$\frac{2\pi kr}{60}.$$

In the position shown in Fig. 30 the wire is moving at right angles to the lines of force, and its rate of cutting the lines is

$$\frac{2\pi kral}{60} \text{ per sec.}$$

But when the coil has moved through an angle  $\alpha$  it no longer cuts across the field at right angles. Its rate of cutting lines is evidently proportional to  $\sin \alpha$ , and we may write for the rate of cutting

$$\frac{2\pi kral}{60} \sin \alpha.$$

But the potential difference is a measure of the rate

of cutting lines of force; and if the potential difference of this coil be  $E'$ , we may write

$$E' = \frac{2\pi kral}{60} \sin \alpha. \quad . \quad . \quad . \quad . \quad . \quad (12)$$

It is evident that this potential difference (since it is proportional to  $\sin \alpha$ ) will vary between zero and a maximum. But this varying potential is of little service in some respects, and we have seen in a previous chapter how it may be transformed into a potential difference which is constant. The value of this potential difference is

$$E = \frac{4\pi kar^*}{60}. \quad . \quad . \quad . \quad . \quad . \quad (13)$$

\* This equation is derived as follows:

Let the angle between the plane of the coil and the lines of the force be  $\alpha$ , and consider that in an infinitesimal time  $dt$  the coil advances through an angle  $d\alpha$ ; then if the brushes be connected through a resistance  $R$ , the quantity of electricity which will flow through the circuit in time  $dt$  is

$$dq = \frac{2\pi karl \sin \alpha \, dt}{60 R}. \quad . \quad . \quad . \quad . \quad . \quad (A)$$

But in the time  $dt$  the coil has moved through an angle  $d\alpha$  and the wire has moved through a space  $= k d\alpha$ ; and since the time is  $dt$ , the velocity is evidently

$$\frac{k d\alpha}{dt}.$$

If now the coil is extended to the opposite side and the two ends brought to a two-part commutator, Fig. 34, the two outside wires are under similar conditions

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Substituting this value in equation (A) for its equivalent,  $\frac{2\pi kr}{60}$  gives

$$dq = \frac{k a l \sin \alpha \, d\alpha}{R}.$$

The quantity of the flow will in one half a revolution diminish to zero and increase again to a maximum ; the second half of the revolution being a repetition of the first except that the direction of flow in the coil is reversed. Therefore the quantity of the flow in moving through  $180^\circ$  is

$$q = \int_0 \frac{k a l}{R} \sin \alpha \, d\alpha. \quad \dots \quad (B)$$

Integrating between these limits gives

$$q = \frac{2k a l}{R} \dots \dots \dots (C)$$

If a constant potential difference act upon the circuit for a time  $t$ , the quantity of the flow will be

$$q = \frac{E t}{R};$$

and since in this case  $t$  is the time of one half-revolution,

$$t = \frac{60}{2r}, \text{ and}$$

and

$$q = \frac{E}{R} \times \frac{60}{2r} \dots \dots \dots (D)$$

except that the direction of the induced potential difference is reversed. Since these two outside wires

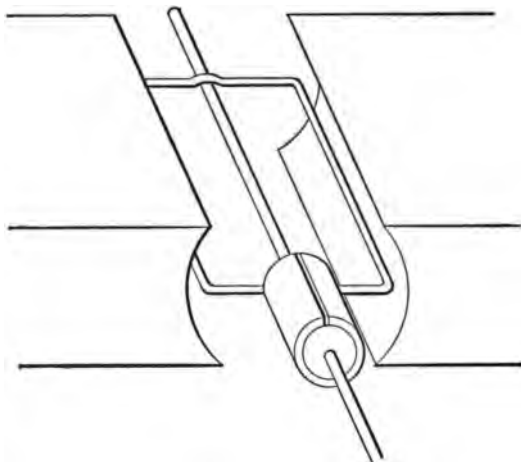


FIG. 34.

are in series, their potential differences are added; and for this arrangement it is evident that

$$E = \frac{8lkar}{60} \dots \dots \dots (14)$$

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Equating these two values of  $q$ , (C) and (D),

$$\frac{E' 60}{R 2r} = \frac{2kal}{R}$$

$$E = \frac{4lkar}{60} \dots \dots \dots (18)$$

The potential difference will be still greater if instead of one turn the coil is composed of a great number of

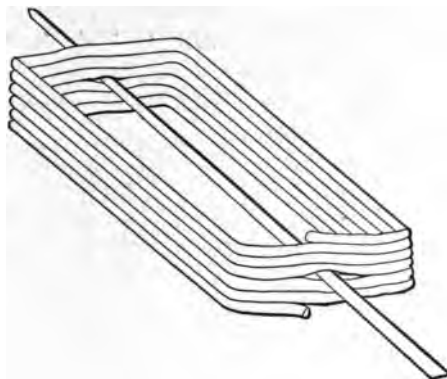


FIG. 35.

turns as shown in Fig. 35. If there are  $n$  turns in the coil, the potential difference will be

$$E = \frac{8lkan}{60}. \quad . \quad . \quad . \quad . \quad . \quad (15)$$

The maximum number of lines of force included in the coil is  $2kal$ , and for this quantity we may write  $\beta$ , the total number of lines of force passing through the armature. Then

$$E = \frac{4rn\beta}{60}. \quad . \quad . \quad . \quad . \quad . \quad (16)$$

This result is in C.G.S. units of potential difference.  
To express the value in volts,

$$E = \frac{.667rn\beta}{10^9}, \quad . \quad . \quad . \quad . \quad . \quad (17)$$

which is the equation for the potential difference of a shuttle-wound armature.

This will have to be modified in order to make it apply to modern armatures. Consider a closed-coil drum armature. We have seen in the earlier part of this work that the potential difference between the brushes of a closed-coil armature is not the sum of the potential differences of the separate coils, but is one half that sum. Therefore we may write

$$E = \frac{.333rn\beta}{10^9}. \quad . \quad . \quad . \quad . \quad . \quad (18)$$

This is the equation for the potential difference of a closed-coil Siemens armature. The equation for a closed-coil Gramme armature is

$$E = \frac{.167rn\beta}{10^9}. \quad . \quad . \quad . \quad . \quad . \quad (19)$$

If in place of  $n$ , the number of turns on the armature, we write  $C$ , the number of conductors counted all round the armature, we may write

$$E = \frac{.167rC\beta}{10^9}. \quad . \quad . \quad . \quad . \quad . \quad (20)$$

This equation applies to either a ring or a drum armature, for it is evident that a drum armature having the same number of turns as a ring armature will have twice the number of external wires.

Let us consider the action of a ring armature in a four-pole field. If the lines of force emanating from each pole is the same as in the machine we have been considering, then each wire of the armature cuts across the same field in one half the time that was required before, and (20) becomes

$$E = \frac{333rC\beta}{10^9}.$$

But the arrangement of the coils is not the same for a four-pole as for a two-pole machine. In the latter the two halves of the armature are connected in multiple and the potential difference of the machine is the same as either half. But in a four-pole machine the coils are arranged in four sets, and these four sets are in multiple. The potential difference of the machine is the same as that of one of the quarters. Therefore our last equation becomes

$$E = \frac{333r \frac{C}{2} \beta}{10^9},$$

or

$$E = \frac{167rC\beta}{10^9},$$

the original form. Similarly it may be shown that this formula will apply to any multipolar field provided the value of  $C$  is suitably taken.

With an open-coil armature the matter is not so simple and depends, not upon the total wires, but upon those in action at one time, and also upon what portion of a revolution they are active. A formula could be derived from this class of armatures by integrating the expression (equation B, footnote page 87) between the proper limits and suitably altering the value  $t = \frac{60}{2r}$ , etc., etc. This will not be done, as there are but few open-coil machines in use, and it is probable that a problem of this character would require special solution, in which case a general formula would be of little service.

Having determined the potential difference generated by an armature and its relation to the total induction it is necessary to investigate the subject of the winding of field coils. Turning to Fig. 32, select some point "A" on the characteristic before the curve becomes too nearly horizontal. Let the co-ordinates of this point be  $H$  and  $\beta$ . If the dynamo is working at this point, the magnetizing force is

$$4\pi nc = H,$$

$$nc = \frac{H}{4\pi}.$$

$$\text{Ampere-turns} = \frac{10H}{4\pi} = .8H.$$

With suitable care in giving values to the different factors this method can be applied to any dynamo. In applying formula 11 to dynamos having a double magnetic circuit (Fig. 30), it must be remembered that the value of  $S_i$  is the sum of the areas of the two fields, and  $d_i$  is the length of the line in one field, and that the fifth term drops out altogether as there is no yoke. It must also be remembered that the ampere-turns will be those required for *each* field. Having now the characteristic of the dynamo on open circuit, it is next desired to find the effect of a current in the armature in order that the proper number of turns may be given to the series coil.

The windings may be determined by the following method :

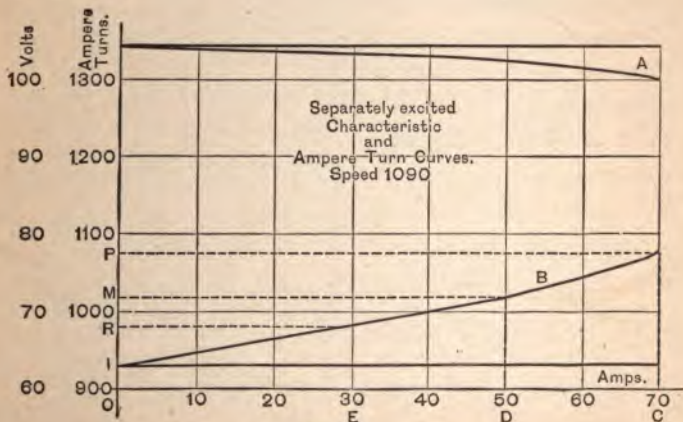


FIG. 36.

Separately excite the machine with a constant current and vary the load on the armature up to the maximum to be required when completed. As the load increases the voltage will diminish. Plot the curve *A* (Fig. 36) with currents in the armature as abscissæ and volts at brushes as ordinates. Now change the field current so as to maintain a constant potential at the brushes, and plot curve *B* with currents in the armature as abscissæ and ampere-turns on field as ordinates.

The curve cutting the axis of ordinates gives the ampere-turns required on open circuit. This is the number required for the shunt coil. At full load *IP* additional ampere-turns will be required; and if *OC* represent the current for this load, the number of turns in the series coil

$$T = \frac{IP}{OC}.$$

For another load *OD*,

$$T = \frac{IM}{OD},$$

and similarly

$$T = \frac{IR}{OC}.$$

Average of these results will give the required turns in the series coil. For most purposes

it is sufficient to determine the value of  $T$  for the maximum current.

It now becomes necessary to know what power will be required to drive the dynamo when completed. The energy of the current is evidently

$$Ec \text{ watts,}$$

where  $E$  = potential in volts at the terminals and  $c$  is the current in amperes flowing. If there were no loss in the conversion, this would be the power required to drive the dynamo. There are, however, losses which must be considered. A certain amount of energy is employed to heat up the conductors. If

$R_a$  = armature resistance,

$R_s$  = field resistance,

$C_a$  = arm current,

$C_s$  = field current,

$c$  = current in external circuit,

$E$  = potential of external circuit,

we may write for a series dynamo

$$C_a = C_s = c.$$

Then the drop of potential over the armature is  $cR_a$ , the drop over the field is  $C_sR_s$ , and the drop over the external circuit is

$$E = cR.$$

$E$  is not the potential difference generated by the armature, but that available in the circuit. The potential generated is in a series dynamo

$$c(R + R_a + R_s).$$

We have seen that this potential difference is

$$\frac{.167rC\beta}{10^9},$$

where  $C$  = conductors counted all around the armature,  $r$  = rev. per min., and  $\beta$  = total induction through the armature.

$$c(R + R_a + R_s) = \frac{.167rC\beta}{10^9},$$

$$c = \frac{.167rC\beta}{10^9(R + R_a + R_s)}, \quad \cdot \quad \cdot \quad \cdot \quad (21)$$

which is the equation of current in a series-wound dynamo. The power lost in heating the armature-coils is  $C^2R_a$ , that in heating the field-coils  $C^2R_s$ . These two losses are known as the wire losses of the machine, and the power required to drive the dynamo has now become

$$Ec + c^2(R_a + R_s).$$

With every revolution of the armature its magnetism is completely reversed and then brought back to the initial condition. There is a certain amount of energy consumed in carrying this mass of iron

through this cycle. A curve is given (Appendix I) showing the energy expended in carrying a cubic centimeter through this cycle of magnetism at different intensities of magnetization. If the radius of the armature-core is  $k$  and its length parallel to the shaft is  $l$ , the volume of iron is  $\pi k^2 l$ ; and since the cycle is completed every revolution, there are  $\frac{r}{60}$  cycles per sec. If  $E_1^*$  represents the power lost (in ergs per sec.) in carrying one cubic centimeter of the iron through a cycle, the power lost in the reversals of the magnetism of the armature is evidently

$$\begin{aligned} & \pi k^2 l \frac{r}{60} E_1 \text{ ergs per sec.} \\ &= .052 k^2 l r E_1 \quad \text{“} \quad \text{“} \quad \text{“} \\ &= \frac{.052 k^2 l r E_1}{10^7} \text{ watts;} \end{aligned}$$

but since about 10 per cent of the armature volume is paper, we should write

$$\text{Iron loss} = \frac{.047 k^2 l r}{10^7} E_1. \quad . \quad . \quad . \quad (22)$$

The power required to drive the dynamo has now increased to

$$Ec + c^2(R_a + R_s) + \frac{.047 k^2 l r}{10^7} E_1.$$

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\* This value  $E_1$  can be read directly from the curve for the corresponding value of  $\beta$  and must not be confounded with  $E$ , the potential difference.

There is one more loss which should be considered, although it is slight. This is the power lost in friction. Representing this loss by  $F$ , we may write as the total power required to drive the dynamo

$$Ec + c^2(R_a + R_s) + \frac{.047k^2lr}{10^7}E_1 + F.$$

If the speed is constant, the factor

$$\frac{.047k^2lr}{10^7}E_1 + F$$

is practically constant. Representing this value by  $K$ , the power required to drive the dynamo may be written

$$HP = \frac{Ec + c^2(R_a + R_s) + K}{746}. \quad (23)$$

The ratio of the useful work given out in the form of electric energy to the total work expended is called the commercial efficiency of the machine. Representing this by  $\eta$ , we may write

$$\eta = \frac{Ec}{Ec + c^2(R_a + R_s) + K}. \quad (24)$$

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1 of determining the value of  $K$  will be given in the  
pg.

It is evident, since  $E$  and  $C$  are included in it, that this value is not constant, but depends on the amount of work the machine is doing. Therefore in speaking of the efficiency of a dynamo it is always advisable to mention the power given out by the machine, as well as its rated capacity.

The difference between the series and the shunt machine is confined to the windings. In case of a shunt machine we may write

$$\begin{aligned}
 C_a &= c + C_s; \\
 E &= \frac{.167rC\beta}{10^9} - C_a R_a \\
 &= \frac{.167rC\beta}{10^9} - R_a(c + C_s) \\
 &= \frac{.167rC\beta}{10^9} - R_a\left(\frac{E}{R} + \frac{E}{R_s}\right), \\
 E\left(1 + \frac{R_a}{R} + \frac{R_a}{R_s}\right) &= \frac{.167rC\beta}{10^9}, \\
 E &= \frac{.167rC\beta}{R_a 10^9} \frac{1}{\frac{1}{R_a} + \frac{1}{R} + \frac{1}{R_s}} \\
 &= \frac{.167rC\beta R R_s}{10^9(R R_s + R_s R_a + R R_a)}; \\
 c = \frac{E}{R} &= \frac{.167rC\beta R_s}{10^9(R R_s + R_s R_a + R R_a)}. \quad (25)
 \end{aligned}$$

Considering the losses which occur in the machine, it is evident that the constant  $K$  will be the same for

562299

## 100 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

a shunt as for a series machine, and we may write for the power required to drive the machine

$$HP = \frac{Ec + C_a^2 R_a + C_s^2 R_s + K}{746}. \quad (26)$$

The commercial efficiency is

$$\eta = \frac{Ec}{EC + C_a^2 R_a + C_s^2 R_s + K}. \quad (27)$$

For a compound-wound dynamo the value of  $K$  will still remain the same, and the power required to drive it will be

$$HP = \frac{Ec + C_a^2 (R_a + R_e) + C_s^2 R_s + K}{746}, \quad (28)$$

where  $R_e$  is the resistance of the series coil, and the commercial efficiency is

$$\eta = \frac{Ec}{EC + C_a^2 (R_a + R_e) + C_s^2 R_s + K}. \quad (29)$$

## CHAPTER VII.

### THE DYNAMO AS A MOTOR.

HAVING now examined the dynamo as a generator, let us consider its characteristics when acting as a motor.

It is evident that the field winding will not be altered. The main difference is that now we have given the fall of potential over the machine or the current and are required to determine at what speed the motor will run and how much useful work it will perform.

We know that when the armature is rotating in a magnetic field it generates a potential difference in direction opposite to that forcing the current through the armature. Representing this counter-electromotive force by  $\epsilon$ , it is evident that in a shunt motor

$C_a = \frac{E - \epsilon}{R_a}$  and the current in the field is  $\frac{E}{R_s}$ . Con-

sidering that the only losses in a motor are those due

to a heating of the conductors, we may write these losses :

$$\text{For the armature } \left( \frac{E - \epsilon}{R_a} \right)^2 R_a.$$

$$\text{For the field coils } \left( \frac{E}{R_s} \right)^2 R_s.$$

Then if  $Ec$  is the electric energy consumed, there is available at the pulley of a shunt motor

$$\begin{aligned} & Ec - \left( \frac{E - \epsilon}{R_a} \right)^2 R_a - \left( \frac{E}{R_s} \right)^2 R_s \text{ watts} \\ &= Ec - \frac{E^2 - 2E\epsilon + \epsilon^2}{R_a} - \frac{E^2}{R_s} \\ &= E \left( \frac{E - \epsilon}{R_a} + \frac{E}{R_s} \right) - \frac{E^2 - 2E\epsilon + \epsilon^2}{R_a} - \frac{E^2}{R_s} \\ &= \frac{E(E - \epsilon)R_s + E^2 R_a - E^2 R_s + 2E\epsilon R_s - \epsilon^2 R_s - E^2 R_a}{R_a R_s} \\ &= \frac{E\epsilon R_s - R_s}{R_a R_s} = \epsilon \left( \frac{E - \epsilon}{R_a} \right) = \epsilon C_a. \end{aligned}$$

If the motor had been series instead of shunt wound, the whole current would pass through the armature and the work done would be

$$EC_a - C_a^2 R_a - C_a^2 R_s.$$

We know that

$$C_a = \frac{E - \epsilon}{R_a + R_s},$$

or

$$E = (R_a + R_s)C_a + \epsilon.$$

Therefore

$$\begin{aligned} C_a^2(R_a + R_s) + \epsilon C_a - C_a^2 R_a - C_a^2 R_s &= \text{work done} \\ &= C_a^2 R_a + C_a^2 R_s + \epsilon C_a - C_a^2 R_a - C_a^2 R_s \\ &= \epsilon C_a, \end{aligned}$$

which is identical with our former equation. That is, the work done by a motor is the product of the counter-electromotive force multiplied by the armature current. The work done by a motor is also equal to

$$\omega T,$$

where  $\omega$  is the angular velocity and  $T$  the torque in pounds at one foot radius.

$$\omega = 2\pi r;$$

$$HP = \frac{2\pi r T}{33000} = \frac{\epsilon C_a}{746} \cdot \cdot \cdot \cdot \cdot \quad (30)$$

We know that

$$\epsilon = \frac{.167rC\beta}{10}.$$

Therefore

$$\begin{aligned}\frac{2\pi rT}{33000} &= \frac{.167rC\beta C_a}{746 \times 10^3}; \\ T &= \frac{33000 \times .167rC\beta C_a}{2\pi r \times 746 \times 10^3} \\ &= \frac{1.18C\beta C_a}{10^3}. \quad . \quad . \quad . \quad . \quad . \quad (31)\end{aligned}$$

The equations for torque may be derived in a different manner and in one which may perhaps be more acceptable to the student.

It has been shown (pages 20 and 21) that if a wire carrying one ampere is moved across a magnetic field at such a rate that one volt is generated, the power required is one watt. If the wire is one centimeter long and the intensity of the field is one line of force per square centimeter, the necessary speed is  $10^8$  centimeters per second (see page 18). Now one watt is  $10^7$  ergs per second, and consequently the work done in moving the wire across the field is  $10^7$  ergs, and this is independent of the speed. In moving  $10^8$  centimeters the wire has cut across  $10^8$  lines of force and the energy expended is  $10^7$  ergs. Therefore for each erg expended moving the wire across the field 10 lines of force have been cut. This action is reversible, and if the motion is caused by the current one erg will be developed for every 10 lines of force cut by a wire carrying one ampere.

If there are  $c$  amperes flowing in the wire, the work performed in cutting 10 lines of force is  $c$  ergs, the work performed in cutting one line is  $\frac{c}{10}$  ergs, and the work performed in cutting  $\beta$  lines is

$$\frac{c\beta}{10} \text{ ergs.}$$

Further, if there are  $C$  wires in place of one and each wire carries  $c$  amperes, the work performed in cutting across the field is

$$\frac{Cc\beta}{10} \text{ ergs.}$$

Now apply this equation to a motor. There are  $C$  wires counted all around the armature, and therefore this factor remains the same. The current in an armature (for a 2-pole field) divides into two equal parts and each wire carries  $\frac{1}{2}C_a$ ; therefore  $c$  may be replaced by  $\frac{C_a}{2}$ .

A wire in the armature cuts across the field twice in one revolution. Therefore we must write  $2\beta$  for  $\beta$ , and the equation becomes

$$\frac{C \times \frac{C_a}{2} \times 2\beta}{10} = \frac{CC_a\beta}{10} \text{ ergs.}$$

But in order to express this value in terms of the radius (which is necessary since torque is a turning moment) we must divide by  $2\pi$  and the expression becomes, representing torque by  $T$ ,

$$T = \frac{CC_a\beta}{10 \times 2\pi} \text{ ergs.}$$

But  $1 \text{ erg} = \frac{7.37265}{10^8} \text{ ft.-lbs.}$ , and consequently in order to express the last equation in pounds at one foot radius we must write

$$\begin{aligned} T &= \frac{CC_a\beta}{10 \times 2\pi} \times \frac{7.37265}{10^8} \\ &= \frac{1.18 CC_a\beta}{10^9}, \end{aligned}$$

which is identical with equation (31). That is, the torque depends only on the number of conductors in the armature, the total induction through the armature, and the armature current, and is independent of speed except to the extent that the speed affects the current by means of the counter-electromotive force.

$$\begin{aligned} \frac{1.18 C\beta}{10^9} \frac{C_a \times 2\pi r}{33000} &= \frac{\epsilon C_a}{746}; \\ r &= \frac{33000}{746} \frac{10^9}{2\pi C\beta \times 1.18} \epsilon \\ &= \frac{59.4}{C\beta} \epsilon 10^8. \quad \dots \dots \dots (32) \end{aligned}$$

That is, the speed of the motor is proportional to the counter-electromotive force, and the torque is proportional to the armature current.

We have seen that for a series motor

$$Ec - c^2(R_a + R_s) = w.$$

This equation may be written

$$c^2(R_a + R_s) - Ec + w = 0;$$

$$c^2 - \frac{Ec}{R_a + R_s} + \frac{w}{R_a + R_s} = 0;$$

$$c^2 - \frac{Ec}{R_a + R_s} + \frac{E^2}{4(R_a + R_s)^2} = \frac{E^2}{4(R_a + R_s)^2} - \frac{w}{R_a + R_s};$$

$$c^2 - \frac{Ec}{R_a + R_s} + \frac{E^2}{4(R_a + R_s)^2} = \frac{E^2 - 4w(R_a + R_s)}{4(R_a + R_s)^2};$$

$$c^2 - \frac{E}{2(R_a + R_s)} = \pm \frac{\sqrt{E^2 - 4w(R_a + R_s)}}{2(R_a + R_s)}.$$

Since a negative value cannot have a square root, the greatest possible value of  $4w(R_a + R_s)$  is  $E^2$ , and consequently the greatest possible value of  $w$  is

$$w = \frac{E^2}{4(R_a + R_s)}.$$

When this is true the last equation becomes

$$c - \frac{E}{2(R_a + R_s)} = 0.$$

## 108 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

Remembering that in a series motor  $c$  and  $C_a$  are identical, we may write for the current flowing in a series motor when maximum work is being performed

$$C_a = \frac{E}{2(R_a + R_s)}.$$

We know that

$$C_a = \frac{E - \epsilon}{R_a + R_s}.$$

Therefore a motor is performing its maximum work when

$$\frac{E - \epsilon}{R_a + R_s} = \frac{E}{2(R_a + R_s)};$$

$$2(E - \epsilon) = E;$$

$$2\epsilon = 2E - E = E;$$

$$\epsilon = \frac{E}{2}.$$

It is now necessary to consider whether this equation is true in a shunt motor. It is known that

$$E(C_a + C_s) - C_a^2 R_a - C_s^2 R_s = w.$$

$$EC_a = EC_s - w - C_s^2 R_s;$$

$$= \frac{EC_s - w - C_s^2 R_s}{R_a};$$

$$C_a - \frac{EC_a}{R_a} + \frac{E^2}{4R_a^2} = \frac{E^2}{4R_a^2} + \frac{EC_s - w - C_s^2 R_s}{R_a};$$

$$\begin{aligned} C_a - \frac{E}{2R_a} &= \pm \sqrt{\frac{E^2 + 4R_a(EC_s - C_s^2 R_s) - 4R_a w}{4R_a^2}}; \\ &= \pm \frac{\sqrt{E^2 + 4R_a(EC_s - C_s^2 R_s) - 4R_a w}}{2R_a}. \end{aligned}$$

Since  $C_s = \frac{E}{R_s}$ , the second term under the radical sign becomes

$$4R_a \left( E \frac{E}{R_s} - \frac{E^2}{R_s} \right) = 0,$$

and the equation may be written

$$C_a - \frac{E}{2R_a} = \pm \frac{\sqrt{E^2 - 4R_a w}}{2R_a}.$$

Following the same course of reasoning as in the series motor, the current flowing when maximum work is being performed is

$$C_a = \frac{E}{2R_a}.$$

In a shunt motor we know that

$$C_a = \frac{E - \epsilon}{R_a}.$$

Therefore, when the motor is performing its maximum work

$$\begin{aligned}\frac{E - \epsilon}{R_a} &= \frac{E}{2R_a}; \\ 2\epsilon &= 2E - E = E. \\ \epsilon &= \frac{E}{2}.\end{aligned}$$

That is, the counter-electromotive force is equal to one half the potential of the mains. We have seen that the efficiency of a motor is

$$\eta = \frac{\epsilon}{E}$$

if the wire losses are assumed to be the only ones. Therefore when a motor is doing its maximum work its efficiency is

$$\eta = \frac{\frac{E}{2}}{E} = 50 \text{ per cent.} \quad . \quad . \quad . \quad . \quad (33)$$

This is known as the law of maximum activity and was for a long time confused with the law of efficiency.

It is due to this misconception that some of the earlier investigators believed the maximum efficiency of an electric motor to be 50 per cent. It is evident at this law has nothing to do with the law of efficiency.

Motors like dynamos may be divided into three classes, series, shunt, and compound wound.

### THE SERIES MOTOR.

This class of motor is used upon both constant-potential and constant-current circuits. It is not self-regulating in either case. When used on constant-potential circuits (as in street-railway systems) the speed is controlled by hand. When used upon constant-current circuits the motors are usually provided with governors to regulate the speed. We have seen that the torque of a motor depends upon the current in the armature and the intensity of the magnetic field in which it revolves (the winding being fixed). Therefore on a constant-current circuit the only factor which can be changed is the strength of field, and this must be weakened as the load diminishes and strengthened as the load increases. The most general method of accomplishing this effect is by means of a centrifugal governor which cuts out layer after layer of the field coils as the load diminishes. It is evident that unless the field is weakened as the resistance to torque diminishes, the motor will race. We have seen, equation (30), that

$$\frac{2\pi r T}{33000} = \frac{\epsilon C_a}{746}.$$

We have also seen that in a dynamo there is a certain loss accounted for by the constant  $K$ . This loss is in watts and, neglecting friction, may be written

$$K = \frac{rg}{60(10)^7},$$

where  $r$  is the number of revolutions per minute and  $g$  is the iron loss in ergs per revolution. Equation (30) is true only when the wire loss is supposed to be the only one and the correction is this constant  $K$ .

$$\frac{2\pi r T}{33000} = \frac{\epsilon C_a - \frac{rg}{60 \times 10^5}}{746}; \quad . . . . . (34)$$

$$T = \frac{(60 \times 10^5 \epsilon C_a - rg) 33000}{60 \times 746 \times 10^7 \times 2\pi r},$$

since  $\epsilon = \frac{.167rC\beta}{10^5};$

$$\begin{aligned} T &= \frac{(60 \times .167rC\beta C_a - 100rg) 33000}{60 \times 100 \times 746 \times 10^7 \times 2\pi r}; \\ &= \frac{1.18C\beta C_a - 11.6g}{(10)^5}. \quad . . . . . (35) \end{aligned}$$

This equation could have been derived by considering equation (31) to give the value of the total torque, the factor  $K$  then becoming

$$K = \frac{rg}{60 \times 10^7}.$$

Or if  $t$  represents the torque required to overcome this loss,

$$\frac{2\pi r t}{33000} = \frac{r g}{60 \times 10^7 \times 746};$$

$$\begin{aligned} t &= \frac{r g 33000}{746 \times 60 \times 10^7 \times 2\pi r} \\ &= \frac{.116g}{10^7}. \end{aligned}$$

Now the useful torque is the total torque minus this waste torque, and we have

$$\begin{aligned} T - t &= \frac{1.18 C \beta C_a}{10^7} - \frac{.116g}{10^7} \\ &= \frac{1.18 C \beta C_a - 11.6g}{10^9}. \end{aligned}$$

Therefore when a series motor is working on a constant current its torque is constant, for the only variable in the above expression is  $B$ , and as this depends directly on  $C_a$  the expression is a constant. The torque being constant, the speed of the motor will evidently not be constant, and if the load is light the motor will race. As has been explained, the speed is maintained approximately constant by cutting out some of the field turns when the load is lightened. The result is a reduction in the

value of  $B$  and a consequent reduction of torque to suit the load. With a series motor operating upon a constant-potential circuit we have a somewhat different effect. The equation of torque is still true, but, the current no longer being constant, the torque will not be constant, and even with the governor mentioned the speed would not be constant. Under these conditions

$$C_a = \frac{E - \epsilon}{R_a + R_s}$$

$$= \frac{E}{R_a + R_s} - \frac{\epsilon}{R_a + R_s} \dots \dots (36)$$

The first term of this expression is a constant, and the current depends upon the value of  $\epsilon$ , since it is evident that the value  $\frac{\epsilon}{R_a + R_s}$  is directly proportional to the speed and strength of field.

Suppose the load on the motor is increased, then the value of  $C_a$  must be increased. If the number of turns of wire on the fields cannot be altered, this can be done only by diminishing the value of  $\epsilon$ , which in turn depends on the speed and strength of field.

The motor being a series machine, it is evident that an increase of  $C_a$  will increase the strength of field, and therefore the speed, being the only other variable, must be reduced. That is, as the torque increases the speed must diminish. A series machine will, there-

fore, not regulate for a constant speed upon a constant potential circuit, but will have a fixed speed for the different loads. This combination is used in street-railway practice, where the torque required to start a car is very heavy.

The variables in equation (35) are  $C_a$  and  $\beta$ , and an increase in either of these factors means an increased torque.

The current in the fields of a series motor is  $C_a$ , the field  $\beta$  depends for its value upon  $C_a$ . Therefore the torque is proportional to  $C_a^2$ . When a series motor is started upon a constant-potential circuit, the current flowing is very great since there is no counter-electromotive force opposing it, and its value depends on  $R_a$  and  $R_s$ . Therefore when a car is started, the torque, depending on the square of this current, is very great.

Different groupings of the field coils and of resistances are effected by a hand-switch, and it is by this method that the speed of the car is controlled. We have seen that the speed of the motor depends on the current, and it may be well to derive an expression for the speed. We know that

$$\epsilon = E - (R_a + R_s)C_a,$$

and also that

$$\epsilon = \frac{.167rC\beta}{10^9}.$$

Combining these two equations,

$$E - (R_a + R_s)C_a = \frac{.167rC\beta}{10^6}$$

$$r = \frac{(E - R_a - R_s)C_a 10^6}{.167C\beta}. \quad . \quad . \quad (37)$$

In designing motors for street-railway service it is necessary to know the weight of motor car and passengers, the speed required, and the maximum grade to be climbed. Having these values, the horse-power required is quickly calculated. Sprague\* gives the formula as

$$HP = \frac{WM}{335} \left( \frac{K}{2000} \pm \sin \vartheta \right), \quad . \quad . \quad (38)$$

where

$W$  = weight of car and passengers in pounds ;

$M$  = speed in miles per hour ;

$K$  = resistance to traction in pounds per ton on a level, and is *about* 25 lbs. per ton ;

$\vartheta$  = angle of grade.

Reckenzaun† prefers an equation of the form

$$HP = \frac{WKS}{33000} \pm \frac{w(.2240S) \sin \vartheta}{33000}, \quad . \quad . \quad (39)$$

where  $w$  is the weight in *tons*, and  $S$  the speed in feet per minute.

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\* *Electrical World*, July 31, 1888.

† *Electrical Engineer*, June, 1888.

## THE SHUNT MOTOR.

Having examined the characteristics of a series motor, let us now take up the shunt motor and study some of its peculiarities. Consider, first, its action when supplied with a constant current. It is evident that before the counter-electromotive force becomes a noticeable factor (that is, at *very* low speeds), the larger part of the current flows through the armature, since the armature resistance is low compared to the resistance of the fields, and that as the speed gradually increases the current in the armature gradually diminishes, while the current in the field circuit gradually increases. This will continue until one half of the current flows through the armature and one half through the field. At this point the motor is doing its maximum work and at but little less than 50 per cent efficiency. When running with no load the speed is very high, the counter-electromotive force is very nearly as great as the initial, and almost the whole current will flow through the field coils. It is evident that this irregularity of speed renders a shunt motor unfit for service on a constant-current circuit. On the other hand, when a shunt motor is supplied with current at a constant potential the speed is fairly uniform. We have the equations

$$C_a = \frac{E - \epsilon}{R_a},$$

and

$$\epsilon = \frac{.167rC\beta}{10^9};$$

therefore we may write

$$C_a = \frac{E - \frac{.167rC\beta}{10^9}}{R_a}.$$

Substituting this value in eq. (35),

$$T = \frac{1.18C\beta \frac{E - .167rC\beta}{10^9}}{R_a} - 1.16g. \quad (40)$$

Now the only two variables in this expression are  $r$  (= rev. per min.) and  $\beta$ . Since the field is supplied at a constant potential and its current is constant independent of what may occur in the armature circuit, the value  $\beta$  may be considered constant. Therefore if an additional load is put upon the motor a greater torque is required, and this can be obtained only by diminishing the speed. Or in other words, the speed of a shunt motor is dependent upon the load being slow for heavy loads and faster for light ones. This variation is, however, very slight and can be reduced almost to zero by keeping the armature resistance very low; for, since

$$C_a = \frac{E - \epsilon}{R_a},$$

it is evident that for a given change in the value of  $\epsilon$  the value of  $C_a$  will be a maximum when  $R_a$  is a minimum. Since

$$\epsilon = \frac{.167rC\beta}{10^9},$$

and the work developed by the motor is

$$HP = \frac{\epsilon C_a - K}{746},$$

$$C_a = \frac{746HP + K}{\epsilon} = \frac{E - \epsilon}{R_a};$$

or

$$(746HP + K)R_a = E\epsilon - \epsilon^2,$$

$$\epsilon^2 - E\epsilon + \frac{E^2}{4} = \frac{E^2}{4} - (746HP + K)R_a,$$

$$\epsilon - \frac{E}{2} = \pm \sqrt{\frac{E^2}{4} - (746HP + K)R_a},$$

$$\epsilon = \frac{E}{2} \pm \sqrt{\frac{E^2}{4} - (746HP + K)R_a}.$$

But we know that

$$\epsilon = \frac{.167rC\beta}{10^9},$$

and may therefore write

$$r = \frac{10^9 \left( \frac{E}{2} \pm \sqrt{\frac{E^2}{4} - (746HP + K)R_a} \right)}{.167C\beta}. \quad (41)$$

### COMPOUND-WOUND MOTORS.

This class of motors have the field excited by two separate coils as in the compound-wound dynamo. In a dynamo the action of the series coil is to increase the strength of field as the load increases, while in a motor the field must be weakened as the load increases in order to reduce the counter-electromotive force (without a reduction in speed) so that more current will flow through the armature to develop for the increased torque. The main objection to this style of motor is that it is liable to reverse its direction of rotation and cause considerable inconvenience. Where this effect (which is due to working with a zero field or nearly so) can be avoided the great constancy of speed makes the motor very desirable. The theory of the windings has been developed by Mr. F. J. Sprague in a very simple manner.\* He gives as the laws of winding for motors having the shunt coil in parallel with the armature alone,

$$\frac{o}{h} = \frac{R_s + R_a}{R_a}; \quad . \quad . \quad . \quad . \quad . \quad (42)$$

but if the shunt coil is connected across the armature and series coil so that the drop over the shunt field will be that over the armature plus that over the series coil, the formula becomes

$$\frac{o}{h} = \frac{R_s}{R_a + R_e}, \quad \cdot \cdot \cdot \cdot \cdot \quad (43)$$

where  $o$  = turns in shunt coil;  $h$  = turns in series coil;  $R_s$  = resistance of shunt field;  $R_a$  = resistance of armature; and  $R_e$  = resistance of series coil.

Mr. Sprague has also shown that motors wound in this manner are self-regulating on either constant current or constant potential. Another way of determining the ratios of the windings is to run the motor with constant speed and varying load, and measuring the ampere-turns in the field for each load. The speed is maintained constant by separately exciting the field and varying the exciting current sufficiently to keep the speed constant. The ampere-turns required for the shunt field will be the number when running empty, and for any load the ampere-turns required for the series coil is the ampere-turns at no load minus the ampere-turns at that load. Curves similar to those plotted for a compound-wound dynamo may be drawn. The reasoning is the same in each case, with the difference that in the dynamo the total ampere-turns is the sum of those of the shunt and the

## 122 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

series coil, while in a motor it is the difference. Compound winding is extremely desirable in a dynamo, but with a motor it is not so necessary, for by making the armature resistance very low the speed will be very nearly constant. In a dynamo the potential should be constant on account of lamps burning, while a few per cent variation in the speed of a motor is in general not objectionable. However, in case a *very* constant speed is required this class of motor may be used with advantage. It should be remembered, however, that a differential action cannot be so efficient as a simple one, and it is therefore to be expected that a compound-wound motor is a little less efficient than a simple shunt motor.

## CHAPTER VIII.

### DESIGN OF ARMATURES.

THE application of the principles and formulæ which have been discussed to the practical design of dynamos and motors may best be explained by a few problems. These will be selected so as to cover as broad a field as possible and to bring out the different principles which have been considered in the previous chapters.

Let it be required to design a 200-light dynamo, the potential difference to be 110 volts and the speed 1500 revolutions per minute.

This problem may be solved in a number of ways. The machine may be a two-pole or a multipolar dynamo. The armature may be a Siemens or a Gramme, and if a two-pole machine is decided upon, the field may be a single magnetic circuit or of the consequent pole type. If the dynamo is to be self-regulating, it will of course be necessary to use a series coil as well as a shunt field.

## 124 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

Before considering these points in detail it is desirable to obtain some further general data which will apply to any of the above constructions.

The average current for a 110-volt lamp (16-candle power) varies from .6 to .65 ampere. Consequently there must be delivered to the circuit

$$200 \times .6 = 120 \text{ amperes,}$$

if the lamps require .6 ampere each, and

$$200 \times .65 = 130 \text{ amperes}$$

if the lamps require .65 ampere each.

It is of course necessary to have a capacity for the higher current, and the rating of the machine must be

$$130 \times 110 = 14,300 \text{ watts.}$$

An allowance must also be made for loss in the conductors, and if this is placed at 5 per cent the actual capacity of the machine must be

$$15,000 \text{ watts.}$$

It is now necessary to confine ourselves to some definite design. Let us first limit the design to a pole dynamo. Equation (20) is

$$E = \frac{.167 Cr \beta}{10^9}.$$

Substituting the given conditions so far as they are known,

$$120 = \frac{.167 \times C \times 1500 \times \beta}{10^9},$$

or

$$C\beta = \frac{120 \times 10^9}{.167 \times 1500} = 480,000,000. \quad . \quad . \quad (A)$$

In the calculation it is necessary to consider the potential as 120 rather than 110 in order to allow for the rheostat included in the field; to counteract the effect of heating and also because the potential generated is not that available at the terminals, but is slightly reduced in overcoming the resistance of the armature.

We have now an indeterminate equation,

$$C\beta = 480,000,000,$$

and evidently an infinite number of values can be given to  $C$  and  $\beta$ , and the equation will still be a true one. In this case we must be governed by experience and a study of the proportions of some dynamo of similar capacity which is known to give satisfactory results. The total induction through the armature increases with the capacity of the machine, of course, but it is not directly proportional to the output. The curve Fig. 37 shows average practice and can be considered approximately correct for drum armatures

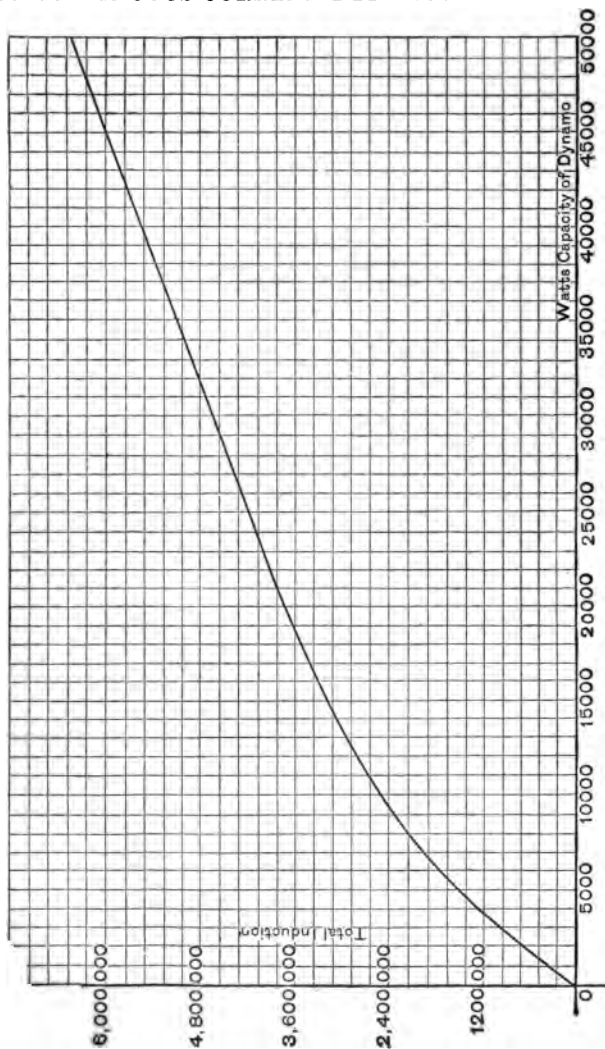


FIG. 37.

in two-pole fields. From this curve it is observed that the total induction through the armature of a 15,000-watt dynamo should be approximately 3,120,000 lines of force. Substituting this value in equation (A) gives

$$C = \frac{480,000,000}{3,120,000} = 154, \text{ nearly. . . . (B)}$$

It should be remembered that this result (B) is only approximate and may be considerably altered by other considerations. Now consider the effect of different types of armature upon the dimensions. Assume first that a Siemens armature is to be used. Evidently  $C = 154$  corresponds to 77 turns of wire. This is not a practicable number at all, and it will be necessary to change it to one which is convenient to wind, and alter the induction through the armature to correspond. In order to retain practically the same proportions the commutator should contain 40 segments, and the armature should be wound with two turns per segment. In all there are 80 turns, and the value of  $C$  becomes 160 in place of 154. This reduces the total induction, equation (A), to

$$\beta = \frac{480,000,000}{160} = 3,000,000. . . . (C)$$

There is considerable difference between the authorities on the question of density of lines in the

armature. Some engineers claim that a density of 75,000 lines per square inch is permissible, and others that the density should not exceed 35,000 lines. The matter depends in a great measure upon the quality of iron. Generally speaking the permeability of iron is very much greater at low densities than at high, and further the hysteresis loss increases very rapidly as the induction attains high values. For these reasons it is well to remain near the lower limit and assume a density of only 40,000 lines per square inch. This density seems to be preferred by American engineers, though the English use a much higher one. At this rate the cross-section of the iron in the armature will be, from equation (C), 75 sq. in. Allowing 10 per cent for lamination gives a total cross-section of 82.5 sq. in. Remembering that these dimensions are only approximate, we may alter them slightly, that is, the cross-section may be slightly reduced and the density increased to counteract the effect. Therefore, if the armature core is made 9 in. in diameter and 9 in. long, practically the same results will be obtained.

The dimensions of the armature are now nearly all determined. The number of coils in the armature, the number of turns per coil, and the diameter and length of core have been decided upon, and the only remaining dimension is the size wire to use. The maximum current in the armature will be 130 amperes. This current is equally divided, half passing through

each side of the armature. Therefore the cross-section need only be sufficient for 65 amperes. The diameter of the core being 9 in., the circumference is 28.27 in. However, it is not the circumference of the core which is to be divided into 160 equal parts, but the circumference of a circle passing through the centres of the wires. Representing by  $x$  the diameter of the wire in inches, the length of this circle is evidently

$$3.1416(9 + x);$$

and also, since the 160 wires are to completely fill the space, we may write

$$x = \frac{3.1416(9 + x)}{160};$$

$$x(160 - 3.1416) = 9 \times .31416;$$

$$x = \frac{28.2744}{156.748} = .18038.$$

This is the diameter of the covered wire; and allowing 10 per cent for insulation, the diameter of the bare wire is

$$.18038 \times .9 = .162342.$$

Referring to a wire table, it will be seen that this is the diameter of No. 6 B. & S. wire. Now if each wire could be wound flat on the core and did not require bending to pass the shaft, the length of a single turn

### 130 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

would be  $9.180 \times 4 = 36.720$ . However, the length of an average turn will be increased by the wire piling up at the end of the armature, and allowing 10 per cent for this increase makes the length of an average turn 40 in. and the total length of wire

$$80 \times 40 = 3200 \text{ in.} = 267 \text{ ft.}$$

The resistance of 1000 ft. of No. 6 wire is .39546 ohm, and the resistance of 267 ft.

$$.39546 \times .267 = .1056 \text{ ohm.}$$

The resistance of the armature is therefore

$$\frac{.1056}{4} = .0264 \text{ ohm.}$$

The watts lost in the armature may be divided into two classes: 1st, wire loss; and 2d, iron loss. The wire loss is

$$c^2 R = (130)^2 .0264 = 405.6 \text{ watts.}$$

The iron loss cannot be calculated exactly, but can be approximately obtained. Considering that the lamination of the armature core has reduced the eddy currents to an amount so small that they may be neglected, the iron loss is due to hysteresis.

A curve is given in Appendix I showing the loss in turning a cubic centimeter of iron through a cycle magnetization at different intensities. Now a

density of 40,000 lines per square inch corresponds to 6666 lines per square centimeter, and it will be observed that the number of ergs lost per cycle at this intensity is (from the curve) 7500. Therefore the iron loss is, from equation (22), reducing inches to centimeters,

$$\frac{.047k^2lr}{10^7}E_1 = \frac{.047 \times (11.43)^2 \times 22.86 \times 1500}{10^7}7500$$

$$= 158 \text{ watts.}$$

Remembering that the wire loss is 405.6 watts, the total loss is

$$406 + 158 = 564 \text{ watts.}$$

The surface of the armature is evidently

$$2\pi k(l + k) \text{ square inches.}$$

$$2\pi \times 4.662(9.324 + 4.662) = 409.7 \text{ square inches.}$$

This is nearly  $1\frac{1}{2}$  watts per square inch of radiating surface. This armature would in all probability overheat considerably, and it is not satisfactory in this respect. Examine the different factors contributing to the heat to be radiated. It is evident, since the speed is fixed and the current also fixed (by the conditions of the problem), that the only remaining variables are armature resistance, volume of iron, and intensity of magnetization,

Now the induction per square centimeter is already quite low and it is not advisable to reduce it any further.

If the volume of iron is reduced, it necessitates either an increase in the induction per square inch, which we have seen is undesirable, or an increase in the number of turns, which, for mechanical reasons, is not desirable. Then, too, a reduction in the volume of iron would involve a reduction in the radiating surface. If by some miracle the iron loss could be reduced to zero, the remaining loss (the wire loss alone) would be 405.6 watts, or one watt per square inch radiating surface. But the iron loss cannot possibly become zero, and for this reason the wire loss must be considerably reduced. Since the current is fixed, this can be done only by reducing the resistance, and this involves an increase in the cross-section of the wire. As opposed to this we have seen that the wire used completely covered the surface of the armature. The cross-section would be considerably increased by winding of No. 4 wire, but it would be impossible to wind this size wire in one layer, as 160 turns require a width of three feet, which corresponds to a diameter of nearly 12 inches and would reduce the length parallel to the shaft to about  $6\frac{1}{2}$  inches. This armature is entirely out of proportion. If the wire were wound in two layers, the width of space required would be about 18 inches, corresponding to a diameter of nearly

6 inches, and the necessary length would be  $13\frac{1}{2}$  inches. This armature is again out of proportion.

If it were necessary that only one layer of wire should be used, the number of turns could be increased and the cross-section of iron reduced, or *vice versa*. In this manner a suitable armature could be designed.

Another expedient suggests itself. The cross-section of No. 7 wire is one half that of No. 4, and consequently two No. 7 wires in multiple may be used. This offers the additional advantage of being more easily handled and the subdivision tends to reduce the foucault currents in the wire. Allowing sufficient space for insulation, 160 No. 7 wires may be wound in 25 inches. This corresponds to a diameter of 8 inches, and the length in order to obtain approximately the same cross-section as before must be 10 inches. The iron loss in the armature core is

$$\frac{.047 \times (10.16)^2 \times 25.4 \times 1500}{10^7} 7500 = 138.6 \text{ watts.}$$

The length of a turn of wire laid flat against the armature is 36 inches, and allowing as before 10 per cent on account of the wire piling up at the ends of the armature, the length of an average turn may be taken as 40 inches. This is assumed to include an allowance for the greater length of a turn on the out-

side layer. The total length of wire on the armature is, therefore,

$$40 \times 160 = 6400 \text{ inches} = 533.3 \text{ feet,}$$

and the resistance of this length is

$$.489845 \times .533 = .26109 \text{ ohms.}$$

Therefore, remembering that there are two wires in multiple, the resistance of the armature is

$$\frac{.26109}{16} = .0163 \text{ ohms.}$$

The wire loss in the armature is

$$(130)^2 \times .0163 = 275.5 \text{ watts,}$$

and the total loss is

$$275.5 + 1386 = 414 \text{ watts.}$$

Considering the cooling effect of rapid rotation, it is perfectly safe to allow one watt for every square inch of radiating surface.

The surface of the armature, not allowing for the increase due to piling up of wire at the ends, is

$$2\pi \times 4.288(10.576 + 4.288) = 400 \text{ square inches.}$$

It must be remembered that the winding increases the surface of the armature. If this effect had not been considered, the surface (that is, the surface of the

core) would have been only 351.8 square inches. We have now designed a Siemens armature which will develop the required potential at the given speed and will not overheat when operating continuously with the full number of lamps. The dimensions are:

Diameter of core.....	8 inches
Length " " .....	10 "
Size wire.....	No. 7 B. & S.
Turns per coil.....	2
Wires in multiple.....	2
Number of coils.....	40

The design of the shaft commutator, etc., are governed by the ordinary rules of machine design and need not be treated here.

Now examine the effect of a change in the type of the armature. Suppose it is decided to have a Gramme armature rather than a Siemens. On account of the hole in the core it is evident that the outside diameter of the armature must be increased in order to obtain the same cross-section of iron. On the other hand, the circumference of the armature increases with the diameter and more turns of wire may be wound upon the core. Consequently not so great a cross-section is necessary. Assume for a first approximation that the diameter of the armature is to be 11 inches. This gives a circumference of 34.6 inches, and in this space we can wind 220 turns of the same size wire used be-

# 136 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

fore (No. 7). Under these circumstances, in order to generate 120 volts it is necessary that the following equation should be true

$$120 = \frac{.167 \times 220 \times 1500 \times \beta}{10^3}$$

$$\beta = 2,170,000.$$

This, allowing 40,000 lines per square inch, gives a necessary cross-section of nearly 55 square inches. Therefore if the length of armature parallel to the shaft is 11 inches and the diameter of the hole is taken as 6 inches, then the proper cross-section of iron will be obtained. Now examine the losses which occur in this armature and also the radiating surface. First the iron loss.

The former value  $\frac{.047k^3lr}{10^7} E_i$  cannot be used in this case, as it applies only to solid cores and must be modified in order to take account of the hole. If the inner diameter of the core (that is, the diameter of the hole) is represented by  $2k_1$ , the true value of the iron loss is

$$\begin{aligned} & \frac{.047(k^3 - k_1^3)rl}{10^7} E_i \\ &= \frac{.047(194.8 - 58.1)1500 \times 27.9}{10^7} 7500, \\ &= 201.7 \text{ watts.} \end{aligned}$$

The length of an average turn around this armature is 28.15 inches, and the length of 440 turns (since there are two wires in multiple) is 1032 feet, which has a resistance of .5144 ohm. Therefore the armature resistance is

$$\frac{.5144}{16} = .032 \text{ ohm.}$$

The wire loss is

$$(130)^2 \times .032 = 540.8 \text{ watts.}$$

The total loss is

$$201.7 + 540.8 = 742.5 \text{ watts.}$$

The question now arising is the surface from which the 742 watts are to be radiated. Evidently if  $r$  is the radius of the outside and  $r_1$  the radius of the hole, the surface is

$$2\pi(lr + r_1l + r^2 - r_1^2),$$

$$6.2832(63.67 + 29.83 + 33.52 - 734) = 751.9 \text{ sq. in.}$$

The rate of radiating is then about 1 watt per square inch, which is perfectly safe and the armature will not overheat. It is evident that this armature could have been designed in many different ways. The length of core parallel to the shaft could have been shorter and the outside diameter greater, etc. etc. In every case the local conditions have a very

great influence on the design. The 220 turns of wire on this armature should be divided into 44 coils of 5 turns each. The data for this armature we have found to be as follows :

Outside diameter of core ..... 11 inches.

Inside        "        "        " ..... 6    "

Length of core parallel to shaft.. 11    "

Number of turns per coil..... 5    "

Number of coils..... 44    "

Wires in multiple..... 2

Size wire..... No. 7 B. & S.

Suppose now that, without making any other change, the armature is connected for a four-pole field. In this case, instead of connecting the two halves of the winding in multiple, the four quarters are so connected. The resistance is evidently  $\frac{1}{4}$  of its former value, or

$$\frac{.032}{4} = .008.$$

Since the magnetism of the armature is now reversed twice as many times as with a two-pole field, the iron loss will be doubled; that is, it will be 403.4 watts. Now to avoid heating, the total loss is confined to 750 watts and consequently the wire loss must be 346.6 watts, or in round numbers 350 watts.

Since the armature resistance is .008 ohm, the current be

$$\sqrt{\frac{350}{.008}} = 209.2 \text{ amperes,}$$

This is a much larger machine than the conditions of the problem call for (having a capacity of 320 lights).

Therefore if a four-pole field is required, the dimensions of the armature must be reduced in order to obtain economical operation. It is clearly a waste of energy to run a 320-light machine on a circuit where the maximum load is to be 200 lamps. The armature may be reduced in size, and besides being more economical to build will also be more economical to operate, since the iron loss will be considerably reduced. The outside diameter of the core may be reduced to, say, 10 inches. The size wire may also be reduced and the number of turns consequently increased. This means that a smaller cross-section of iron may be used, and consequently the iron loss reduced. It has the further advantage of reducing the expense of building. If the armature is to be wound of No. 10 wire, 280 turns may be wound upon the core in one layer. This may be divided into 40 coils of 7 turns each. There should be two layers of wire in order that there may be two wires in multiple. Since the speed is 1500 rev. per min.,

$$120 = \frac{.167 \times 280 \times 1500 \times \beta}{10^9},$$

or

$$\beta = 1,700,000.$$

## 140 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

If the diameter of the hole in the armature is taken as  $5\frac{1}{2}$  inches and the length parallel to the shaft as 9, the cross-section is 40.5 square inches. This gives a density a little greater than 40,000 lines per square inch, but is perfectly safe as 40,000 is not a rigid limit. Remembering that the magnetism of the armature core is reversed twice as many times in a four-pole as in a two-pole field, we may write for the iron loss

$$\begin{aligned} & \frac{.094(k^2 - k_1^2)lr}{10^7} \\ &= \frac{.094[(12.7)^2 - (6.98)^2] \times 1500 \times 22.86}{10^7} 7500 \\ &= 272 \text{ watts.} \end{aligned}$$

The length of an average turn of wire is 23.3 inches, and of the 560 turns is 13,048 inches or 1087 feet.

The armature resistance is

$$\frac{1.087 \times .999}{64} = .017 \text{ ohm.}$$

The wire loss with 130 amperes is

$$(130)^2 \times .017 = 287 \text{ watts.}$$

The total loss is therefore

$$272 + 287 = 559.$$

The surface of the armature is

$$2\pi[5.204 \times 9.408 + 2.526 \times 9.408 + (5.204)^2 - (2.526)^2]$$

$$= 586.9 \text{ square inches.}$$

This allows a little over 1 square inch per watt to be radiated, and the armature will not overheat. We may therefore consider the dimensions of the armature as satisfactory. They are:

Outside diameter.....	10 inches.
Inside " .....	5½ "
Length parallel to shaft.....	9 "
Number of coils.....	40
Turns per coil .....	7
Size wire.....	No. 10 B. & S.
Wires in multiple.....	2

We have now designed an armature of each of the three different classes; it is only necessary to provide a field in order to complete the principal features of the design.

## CHAPTER IX.

### DESIGN OF FIELD MAGNETS.

IN the preceding chapter the diameter of the completed armature was not determined; that is, no allowance was made for insulating the core or for the binding wires.

The diameter of the Siemens armature core considered is 8 inches, and the space required for four layers (two on each side of the armature) of No. 7 wire is .63 inch. Allowing  $\frac{3}{16}$  inch on each side for insulation, binding wires, and clearance gives 9 inches as the necessary bore of the field for this armature.

Suppose the type of field to be used is a single magnetic circuit, what will be the necessary cross-section of iron?

In order for the armature to generate the required total difference at the given speed it is necessary that the total induction through the armature shall be 10 C. G. S. lines of force. It is known that

there will be a certain amount of leakage of the lines, and it will be necessary to provide a greater induction in the fields than is required in the armature. For this type of dynamo Hopkinson has given the ratio of total lines in the field to useful lines in the armature as 1.32. Therefore the fields must be of sufficient cross-section for

$$3,000,000 \times 1.32 = 3,960,000 \text{ lines.}$$

The number of lines per square inch in the field may be much greater in the field magnets than in the armature. In the armature the number was limited, not by saturation, but by the hysteretic loss. In the field, there being no reversal of magnetism, this factor does not appear, and the density may be as high as 70,000 lines per square inch. This gives a necessary cross-section of 56.6 sq. in., or a diameter of  $8\frac{1}{2}$  in.

In order to construct the characteristic of the machine it is necessary to assume some dimensions. From the drawing of the machine, Fig. 38, the following dimensions are taken :

*Armature.*—Cross-section =  $8 \times 10 = 80$  sq. in. = 516 sq. cm. Length of an average line of force = 6.8 in. = 17.3 cm. Therefore, allowing for lamination,

$$S_f = 464 \text{ sq. cm. and } d_f = 17.3 \text{ cm.}$$

*Air-space.*—Cross-section =  $11.5 \times 10 = 115$  sq. in. = 741.8 sq. cm.; the length of a line of force is  $\frac{1}{2}$  in.

# 144 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

= 1.27 cm. Allowing 13 per cent for dissipation of the field,

$$S_f = 838.2 \text{ sq. cm. and } d_f = 1.27 \text{ cm.}$$

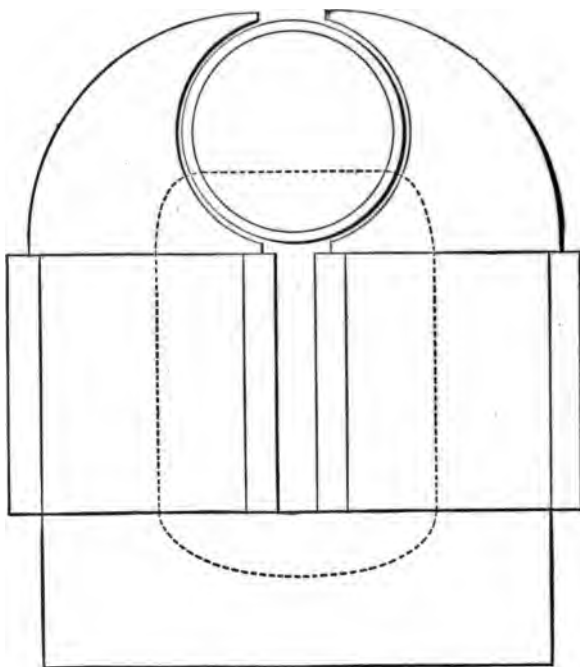


FIG. 38.

*Pole-piece.*—On account of its irregular form the cross-section and length cannot be measured exactly. Taken as

$$S_p = 550 \text{ sq. cm. and } d_p = 8.9 \text{ cm.}$$

*Field.*—There is no uncertainty concerning these factors. The cross-section is 56.6 sq. in. and the length 10 in. This gives

$$S_4 = 365.7 \text{ sq. cm. and } d_4 = 25.4 \text{ cm.}$$

*Yoke.*—The bed-plate in this machine forms the yoke, and the values may be taken as

$$S_5 = 500 \text{ sq. cm. and } d_5 = 35.5 \text{ cm.}$$

The ratio of the number of lines of force in the poles to the number in the armature may be taken as 1.3, and the factor for the yoke is practically the same. Therefore we may write

$$\begin{aligned} 4\pi nc = 17.3 \frac{\beta}{464\mu_1} + 2.54 \frac{\beta}{838.2} + 17.8 \frac{1.3\beta}{550\mu_2} \\ + 50.8 \frac{1.32\beta}{365.7\mu_4} + 35.5 \frac{1.3\beta}{500\mu_5}. \end{aligned}$$

We have seen (page 80) that this equation may be subdivided, and a curve representing each portion of the magnetic circuit may be plotted.

The general form of the subdivided equation is

$$x = \frac{d\beta}{S\mu},$$

where  $x$  is the magnetizing power required,  $d$  is the length of an average line of force in this portion

of the circuit,  $\beta$  the total induction in C. G. S. lines,  $S$  the cross-section of the circuit, and  $\mu$  the permeability of the iron used.

Of these factors  $d$  and  $S$  are known, various values are given to  $x$ , and the corresponding values of  $\beta$  calculated;  $\mu$  depends upon  $x$  for its value and may be read from the curves (Appendix I) for the different irons, cast, sheet, and wrought. It also depends on  $d$ , since the magnetizing power in the curves are per unit of length. Therefore, in taking the values of  $\mu$  from the curve, the value of  $H$  is  $\frac{x}{d}$ .

#### FOR THE ARMATURE.

$$x_1 = \frac{17.3\beta}{464\mu_1}, \quad \beta = \frac{464}{17.3}\mu_1 x_1 = 26.8\mu_1 x_1.$$

The values of  $\mu_1$  must be taken from the curve for sheet iron.

$x_1$	$\frac{x_1}{d_1}$	$\mu_1$	$\beta$
200	11.56	910	4,877,600
400	23.12	560	6,003,200
600	34.68	400	6,432,000
9	46.24	318	6,817,920
	57.80	261	6,994,800

## FOR THE AIR-SPACE.

$$x_2 = \frac{2.54\beta}{838.2}, \quad \beta = \frac{838.2}{2.54} x_2 = 330x_2.$$

This equation represents a straight line passing through the origin. It is therefore necessary to determine only one point, preferably one of high coördinates.

$x_2$	$\beta$
10,000	3,300,000

## FOR THE POLE-PIECES.

$$x_2 = \frac{17.8 \times 1.3\beta}{550 \mu_2}, \quad \beta = \frac{550}{23.14} \mu_2 x_2 = 23.77 \mu_2 x_2.$$

The values of  $\mu_2$  must be taken from the curve for cast iron.

$x_2$	$\frac{x_2}{2d_2}$	$\mu_2$	$\beta$
400	22.48	194	1,844,552
600	33.72	170	2,424,540
800	44.96	148	2,814,368
1000	56.20	131	3,113,870
1500	84.3	104	3,708,120

## FOR THE FIELD CURVES.

$$x_4 = \frac{50.8 \times 1.32\beta}{365.7 \mu_4}, \quad \beta = \frac{365.7}{67} \mu_4 x_4 = 5.46 \mu_4 x_4.$$

# 148 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

The values of  $\mu_1$  must be taken from the curve for wrought-iron.

$x_1$	$\frac{x_1}{2d_1}$	$\mu_1$	$\beta$
400	7.88	1140	2,489,760
600	11.82	910	2,981,160
800	15.76	760	3,319,680
1000	19.70	650	3,549,000
1500	29.55	470	3,849,300

## FOR THE YOKE.

$$x_2 = \frac{30.5 \times 1.3\beta}{500\mu_2}, \quad \beta = \frac{500}{39.65} \mu_2 x_2 = 12.6 \mu_2 x_2.$$

The values of  $\mu_2$  must be taken from the curve for cast-iron.

$x$	$\frac{x}{d_2}$	$\mu$	$\beta$
800	26.23	185	1,864,800
1000	32.80	172	2,167,200
1500	49.20	142	2,683,800
2000	65.60	122	3,074,400

Having now all the necessary data, the curves of the machine (Fig. 39) may be drawn. From the characteristic the required magnetizing power may be determined. Representing its value by  $H$ ,

$$4\pi nc = H.$$

But this gives the value in absolute units, and it may be written

$$\text{ampere-turns} = \frac{10H}{4\pi} = .8H.$$

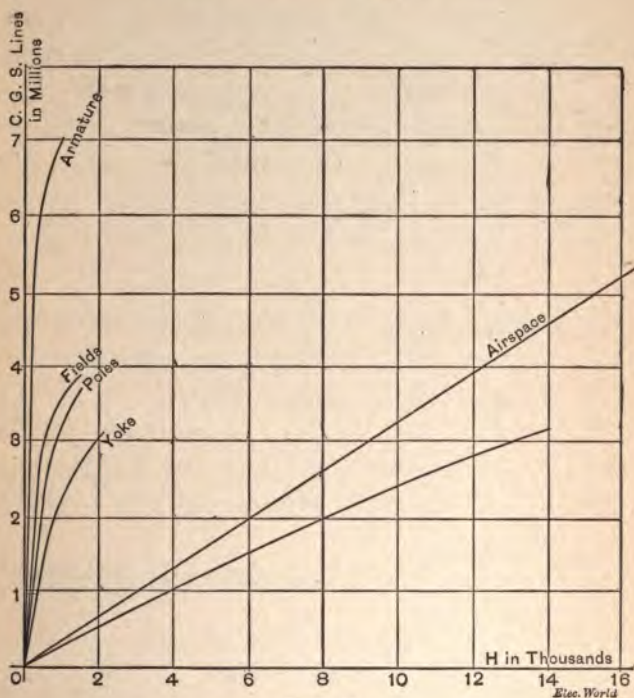


FIG. 39.

In order to establish a total induction of 3,000,000 lines through the armature, it is necessary to have a magnetizing power of  $H = 12,800$ , or

10,240 ampere-turns.

surface, and the fields of this machine will remain at a much lower temperature than is really necessary.

We have now determined the principal dimensions of a machine which will meet the requirements of the problem.

But the engineer should not rest contented with designing a machine that will perform the work required. He should carefully examine the dynamo, and if possible so alter it that it may be more economically constructed or be more efficient. It is at this point that the value of Hopkinson's method of plotting the characteristic curve is appreciated. The different portions of the machine can be examined, and the effect of an alteration in one or more of them determined.

Turning to the curve, Fig. 39, we notice that the magnetizing power required for the armature is small compared to that required for the remaining portions of the magnetic circuit. We have seen (in the last chapter) that the armature will not overheat. Therefore the design of the armature may be considered satisfactory and the other parts examined. The dimensions of the air-space are fixed by the armature, and therefore cannot be altered. The field cores require less magnetizing power than the poles and yokes, but more than the armature. The length of the circuit in the poles cannot very well be shortened, its cross-section cannot be increased without

increasing the diameter of the field cores. An increase in the diameter of the field cores means a greater length of wire per turn, and consequently an increase in the cost of copper in the field. If the diameter of the field core is increased to 9 in., the cross-section of the pole may be increased about 35 sq. cm., making the new cross-section  $S_3 = 585$  sq. cm. The length of the circuit will be increased slightly and may be taken as  $d_3 = 9.2$  cm. The data for plotting the curve of the new pole-piece are

$$x_3 = \frac{18.4 \times 1.3\beta}{585A}. \quad \beta = \frac{585}{23.92} \mu, x_3 = 24.46 \mu, x_3.$$

$x_3$	$\frac{x_3}{2d_3}$	$\mu_3$	$\beta$
400	21.74	196	1,917,664
600	32.61	173	2,538,948
800	43.48	152	2,974,336
1000	54.35	133	3,253,180
1500	81.52	107	3,925,830

This curve (Fig. 40) is a little better than the first one, and is probably as nearly perfect as it can be made under the circumstances.

The diameter of the field cores having been increased to 9 in., the cross-section is 410.8 sq. cm. Let us now consider the length of the core. It is only necessary to have a core of sufficient length to contain

## 154 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

the requisite number of turns of wire. We have seen that the cores in the first approximation gave a field of the required strength, and yet consumed less than

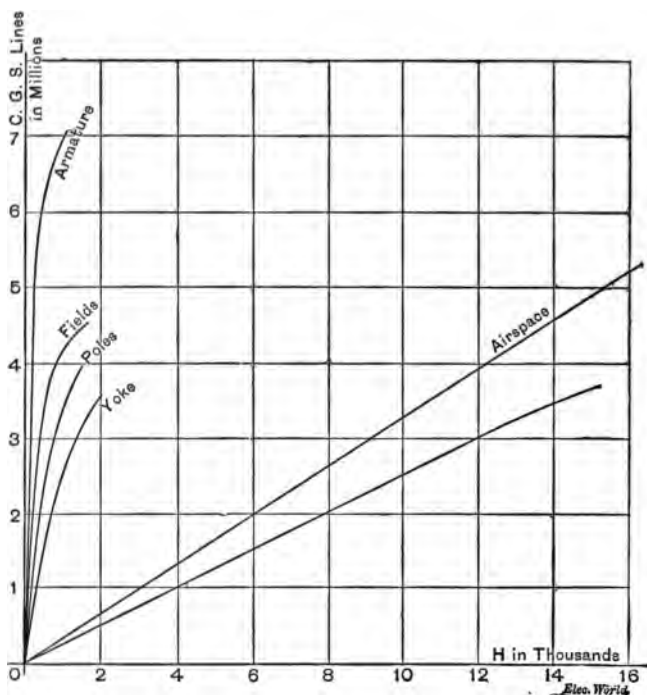


FIG. 40.

1 per cent of the power for the field. Therefore the cores can be shortened considerably. This will also interbalance the increased length of an average

turn by reducing the total number of turns. Take the length of core as 8 in. or 20.3 cm. The equations of the new field cores are

$$x_4 = \frac{40.6 \times 1.32\beta}{410.8\mu_4}, \quad \beta = \frac{410.8}{536}\mu_4 x_4 = 7.66\mu_4 x_4.$$

$x_4$	$\frac{x_4}{40.6}$	$\mu_4$	$\beta$
400	9.85	1010	3,094,640
600	14.77	790	3,630,840
800	19.70	650	3,983,200
1000	24.62	540	4,136,400
1500	36.93	385	4,423,650

The only remaining part is the yoke, and this is very much out of proportion, requiring a very large magnetizing power compared to the other parts.

The width of the yoke proper may be made 10 in. and the depth also 10 in., giving 100 sq. in. cross-section. To this must be added say 10 sq. in., on account of the bed-plate forming part of the magnetic circuit. This gives a cross-section of 710 sq. cm. The length of the magnetic circuit has increased but slightly and may be taken as 32.5 cm. The equations of the new yoke are

$$x_4 = \frac{32.5 \times 1.32\beta}{710\mu_4}, \quad \beta = \frac{710}{42.2}\mu_4 x_4 = 14.06\mu_4 x_4.$$

# 156 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

$x_s$	$\frac{x_s}{82.5}$	$\mu_s$	$\beta$
800	24.6	188	2,114,624
1000	30.75	177	2,488,620
1500	46.12	146	3,079,140
2000	61.50	125	3,515,000

From the curves of this machine (Fig. 40) we find the magnetizing power required for 3,000,000 lines of force to be  $H = 12,000$ , or

9600 ampere-turns.

Now proceed as in the former case to find the size of wire. Since so small a per cent of the total power was required for the field, we may safely assume that a thickness of  $1\frac{1}{2}$  in. for the winding is not necessary. Reducing this to one inch will save considerable copper; then

$$9600 = \frac{\alpha}{\sqrt{9 \times 11}},$$

$$\alpha = 96,000.$$

As before, this value lies between No. 17 and No. 16 wire. Using the larger size we can wind on each spool 20 layers of 134 turns each, or 5360 turns on the two spools. The resistance of the two spools in series is

$$\frac{\pi \times 10 \times 5.36 \times 4.02}{12} = 56.4 \text{ ohms.}$$

The field current is 2.13 amperes and the loss in the field is 255.6 watts. The radiating surface of the coils is

$$2\pi \times 11 \times 75 = 518 \text{ sq. in.}$$

This allows two square inches for every watt lost, and consequently the fields will not overheat.

This machine is a very great improvement on the original one. The working point is on the straight portion of the characteristic, and the regulation should therefore be satisfactory. The curves for the field and armature are exceedingly good, but those for the yoke and pole-pieces are not quite so satisfactory. Indeed, it would be an advantage to move the fields nearer together, and in this way to shorten the length of the yoke.

It is thought that the method of designing fields has been sufficiently illustrated, and that it will therefore be unnecessary to complete the calculations for the remaining two machines (Figs. 41 and 42). The leakage coefficient may be taken as 1.6 in either case. This is an average value and will be a sufficiently close approximation for nearly all cases.

There are one or two points on which it is necessary to caution the student in the design of these machines.

Consider the consequent-pole machine (Fig. 41) with a ring armature.

There are two distinct magnetic circuits in multiple.

## 158 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

This gives rise to two methods of constructing the curve, which, though different in minor points, give the same result. The first is to construct the curves for one side of the machine only, and to duplicate the results for the other side. The second method is to

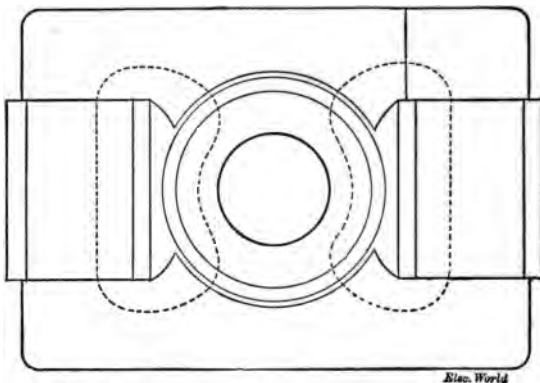


FIG. 41.

obtain curves for the machine as a whole. The same final result will be obtained whichever method is followed. Following first method :

*Armature.*—The cross-section of the armature must be considered as that of one side. That is, if the outside diameter of the armature core is 11 in., the inside diameter 6 in., and the length 11 in., the cross-section to be considered is

$$\frac{(11 - 6) \times 11}{2} = 27.5 \text{ sq. in.}$$

The length of the line is easily obtained from the figure.

*Air-space.*—There can be no doubt as to the length of the circuit in this portion. It is twice the radial distance between the bore of the fields and the surface of the core. The cross-section is *one half* the area of the bore of one pole plus the usual allowance for dissipation of field.

*Pole-pieces.*—The cross-section may be taken on the section indicated by the line *b*. The length of a line is *twice* the length in *one* pole.

*Field.*—The cross-section is  $\pi$  times the square of the radius. The length is shown in the figure.

The ampere-turns given by this construction are those required for each field, and the induction should be one half the total induction required.

Following the second method, it is only necessary to double all the areas and keep the lengths the same as in the first method.

In this construction also the ampere-turns obtained are those required for each field, but the induction is the total induction required.

In Fig. 42, for a four-pole field, the conditions, are somewhat different.

*Armature.*—The cross-section of the armature, as well as the length, should be taken the same as in the second method for the consequent-pole type.

*Air-space.*—The cross-section may be taken as the

## 160 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

area of the face of one pole plus the usual allowance for dissipation. The length is twice the radial distance between the armature and the face of the pole.

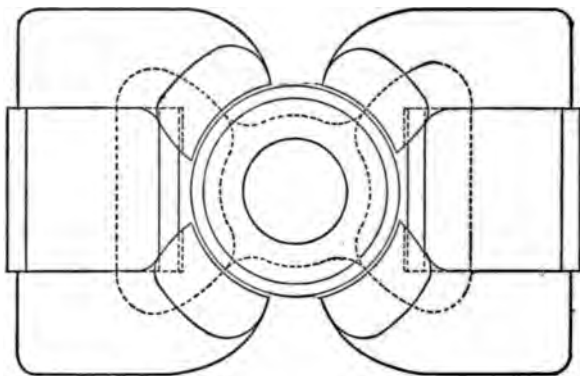


FIG. 42.

*Poles.*—The *cross-section* is that of *one* pole, and the *length* double that for *one* pole.

*Field.*—The *cross-section* is  $\pi$  times the square of the radius, the *length* being the same as in consequent pole machine.

The ampere-turns given by this construction are those required for each field. The induction is the total induction.

## CHAPTER X.

### DESIGN OF MOTORS.

It is not the intention, in this chapter, to discuss the magnetic circuit of a motor. The proportions of the circuit are the same in a dynamo as in a motor, and are governed by the same principles. Many problems in motor design may be resolved into designing a dynamo which will, when supplied with electricity (at a given potential or of a given current strength), develop the required power at the given speed. There is one factor entering into the calculations which has more influence on the action of a motor than on the performance of a dynamo. This factor is commercial efficiency.

In a dynamo, if the commercial efficiency is lower than allowed for, it means that more power will be required to drive the machine. It also means an increased heating in some portion. But if the armature is driven at the given speed and the field intensity remains constant, the dynamo will continue to

develop electric energy at approximately the same potential, and the energy developed is practically constant under the same conditions.

This is not true with a motor. If the efficiency of a motor is lowered, the same increase in heating may be noticed ; and even though the potential (or current) remains constant, there will be a reduction in the speed.

Therefore it is necessary, in designing a motor, to make a first approximation of the dimensions for the required speed and power, and afterward to make such alterations as the nature of the problem may demand.

The uncertain factor entering into the calculations is the power required to overcome friction. This is so small a proportion of the total power that any variation may be counteracted by a slight change in the field.

Let it be required to design a 10 H.-P. motor which will make 1600 revolutions per minute when supplied with electricity at a constant potential of 110 volts, the commercial efficiency to be not less than 85 per cent

$$10HP = 7460 \text{ watts.}$$

Since this is the energy developed, the energy drawn from the line is

$$\frac{7460}{.85} = 8775 \text{ watts.}$$

It is safe to allow 5 per cent of this power for wire losses. The total loss is

$$8776 \times .15 = 1316.4 \text{ watts.}$$

The wire loss is

$$8776 \times .05 = 438.8.$$

The remaining loss is

$$1316.4 - 438.8 = 877.6 \text{ watts.}$$

This is the factor  $K$  mentioned on page 112, and may be written

$$\begin{aligned} 877.6 &= \frac{1600g}{60(10)^7}; \\ g &= \frac{60 \times 877.6 \times 10^7}{1600} \\ &= 329,000,000. \end{aligned}$$

But we know that

$$\begin{aligned} \frac{2\pi \times 1600 \times T}{33,000} &= 10; \\ T &= \frac{330,000}{2\pi \times 1600} = 32.8. \end{aligned}$$

Substituting this value of  $T$  in equation (35),

$$\begin{aligned} 32.8 &= \frac{1.18C\beta C_a - 11.6 \times 329,000,000}{10^9}; \\ C\beta &= \frac{32.8 \times 10^9 + 11.6 \times 329,000,000}{1.18C_a}. \end{aligned}$$

## 164 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

If  $2\frac{1}{2}$  per cent of the power delivered to the motor is expended in the field, the energy delivered to the armature is

$$8776 \times .975 = 8556.6 \text{ watts};$$

and since the potential is 110 volts,

$$C_a = \frac{8556.6}{110} = 77.8 \text{ amperes.}$$

Substituting this value,

$$C\beta = \frac{32.8 \times 10^9 + 11.6 \times 329,000,000}{1.18 \times 77.8} = 400,000,000.$$

From the curve, page 126, we find that it is customary for a drum armature in a two-pole field to have a total induction of

$$\beta = 2,200,000 \text{ C. G. S. lines}$$

for a machine of this size. Substituting this value of  $\beta$  in the above equation, we find  $C = 182$ .

This corresponds to 91 turns. But this is not a practicable number, and must therefore be slightly altered. Assume 48 coils of two turns each. Then

$$C = 192$$

and

$$\beta = \frac{400,000,000}{192} = 2,083,800.$$

Allowing 40,000 lines per square inch gives a cross-section of 52 sq. in.

The core of the armature may be taken as 7 in. in diameter and 8 in. long. The length of an average turn of wire is about three feet, and the total length of wire on the armature 288 ft. If the armature is wound with two layers of wire, the space allowed for each wire is

$$x = \frac{\pi(7+x)}{96};$$

$$x(96 - \pi) = 7\pi;$$

$$x = \frac{21.9912}{92.8584} = .237 \text{ in.};$$

or, allowing 10 per cent for insulation, the diameter of the bare wire is .213 in. The nearest diameter in the wire table smaller than this is .204, the diameter of No. 4 wire. The resistance of 1000 feet of this wire is .24858, and consequently the armature resistance is

$$\frac{.24858 \times .288}{4} = .018 \text{ ohm.}$$

We have seen that

$$C_a = \frac{E - \epsilon}{R_a}.$$

# 166 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

Substituting the known values in this equation,

$$77.8 = \frac{110 - \epsilon}{.018};$$

$$\epsilon = 110 - 1.4 = 108.6.$$

We are now in a position to finally calculate the total induction through the armature.

From equation (20), page 90,

$$108.6 = \frac{.167 \times 1600 \times 192 \times \beta}{10^9};$$

$$\beta = \frac{108.6 \times 10^9}{.167 \times 1600 \times 192}$$

$$= 2,100,000.$$

The induction through 1 sq. cm. of iron is 6500 C. G. S. lines of force, and the value of  $E_1$  (taken from the curve, Appendix I) is 7200. Consequently the iron loss in the armature is

$$\frac{.047k^2lr}{10^7} E_1 = \frac{.047 \times (8.9)^2 \times 20.3 \times 1600}{10^7} 7200$$

$$= 185 \text{ watts.}$$

The wire loss is

$$(77.8)^2 \times .018 = 109 \text{ watts,}$$

and the total loss in the armature is 294 watts. The face of the armature is over 300 sq. in., and the

armature therefore will not overheat. The dimensions of the field may be determined in exactly the same manner as though the machine were to be used as a dynamo. The method explained in the last chapter will give the necessary windings of the shunt field, and if it is desired to compound the machine it is very easily accomplished according to the laws given on page 120.

It may be well to call attention to the error resulting from considering the efficiency of a motor as  $\frac{e}{E}$ , as is given in so many text-books; or, rather, to point out that "electrical efficiency" is a meaningless term. For according to this expression, the efficiency of the motor is

$$\frac{108.6}{110} = 98.7 \text{ per cent.}$$

If the motor is to run on a constant-current circuit of 10 amperes and is required to develop the same power at the same speed, it will be necessary to increase the number of turns on the armature.

If the armature is wound with the same number of coils and each coil has 16 turns instead of 2, the value of  $C$  becomes 1536, and the torque is

$$T = \frac{1.18 \times 1536 \times 2,100,000 \times 10 - 11.6 \times 329,000,000}{10^9}$$

$$= 34.25 \text{ lbs.};$$

## 168 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

and if the motor is so loaded that it runs at a speed of 1600 revolutions per minute, the horse-power developed is

$$HP = \frac{2\pi \times 1600 \times 34.25}{33,000} = 10.4.$$

Of course it will be necessary to have a governor which will weaken the field as the load is diminished, the horse-power and windings determined being for a maximum load.

It will be necessary for convenience in construction to make several small changes in the different portions of the machine. For in order to wind 768 turns of wire on the armature it would be necessary to wind three layers of wire, and while this could be done it is desirable to have if possible an even number of layers. Remembering that by increasing the number of turns in the armature a reduction in the value of  $\beta$  is rendered necessary, the student should experience no difficulty in making the necessary alterations.

## CHAPTER XI.

### DYNAMO AND MOTOR TESTING.

HAVING considered the laws governing the economic design of dynamos and motors, and derived the equations of potential difference, efficiency, etc., it is desirable to discuss the methods of testing the completed machine.

By the term "testing" is meant not only the subjection of the machine to its normal working conditions for a stated period, but also a careful investigation of its characteristics and the effect of various changes in the design or operation. The subject, therefore, resolves itself into a series of problems, and each being in itself complete, there is no particular order in which the different tests need be considered.

The results of the tests can generally be plotted as curves showing the relation existing between two quantities. The curves discussed in this chapter are not the only ones that may be plotted. Nor is it

probable that all of those given will be taken from one machine. Various lines of experiment will suggest themselves to the investigator, and the purpose for which the machine was designed will govern the nature of the tests to be made.

### CHARACTERISTIC CURVE.

The curve showing the relation between the current in the external circuit and the potential difference at the terminals of a dynamo is known as the characteristic curve of the machine.

The general form of this curve for a series dynamo is shown in curve *A*, Fig. 43. It will be observed that the curve rises very rapidly at first, attains a maximum, and eventually bends down. This action is easily explained. With small currents the iron in the circuit is at a low density and the permeability is quite high. Therefore a slight change in the magnetizing force produces a marked change in the induction, and consequently in the potential difference. As the iron approaches saturation its permeability diminishes, and the curve approaches a horizontal line. Were there no armature effect the curve would ultimately become a horizontal line and remain so. As the armature current increases, the reaction becomes more pronounced; and when this effect more than counterbalances the small increase in the magnetism of the

fields, the number of lines of force in the armature actually diminishes, and the curve therefore bends down. The other curves shown in Fig. 43 may be derived from curve *A* by applying Ohm's law.

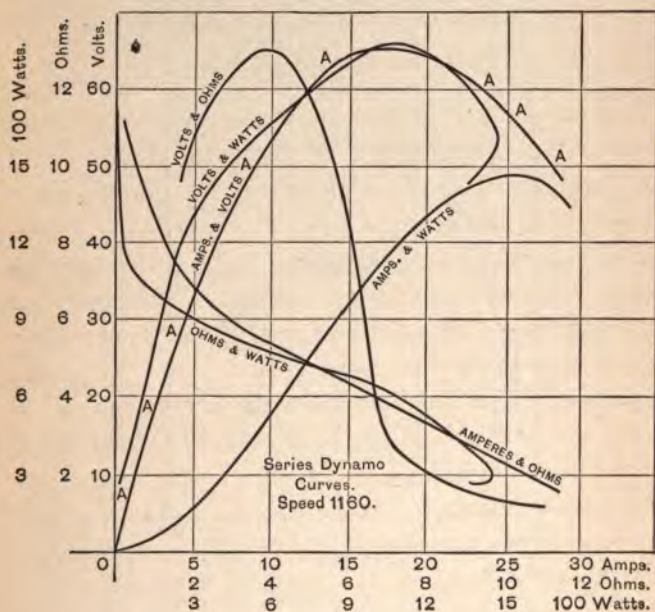


FIG. 43.

The effect of speed upon the characteristic is shown in Fig. 44. It will be seen that the general form of the curve is the same for high and low speeds.

The characteristic curve of a shunt dynamo (Fig. 45)

## 172 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

is very different from that of a series machine. At first the curve is nearly horizontal, but as the load increases the potential diminishes. It will also be

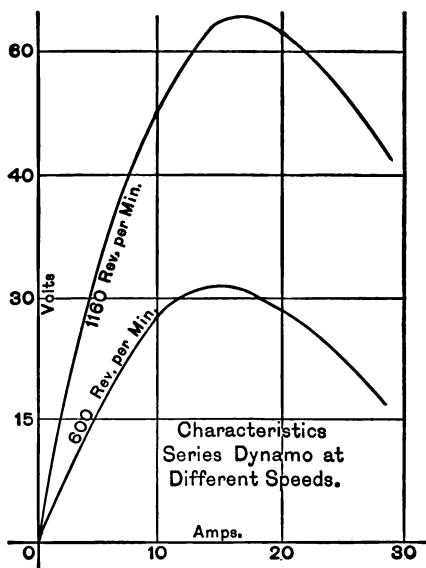


FIG. 44.

noticed that the machine has a maximum current, and even though the resistance of the external circuit should be reduced beyond the point which gives this current, there will be no increase in the current strength. Indeed, if the curve is continued it bends back and ultimately passes through the origin. This

effect is due partly to armature reactions and partly to the shunting of the field coils by the external cir-

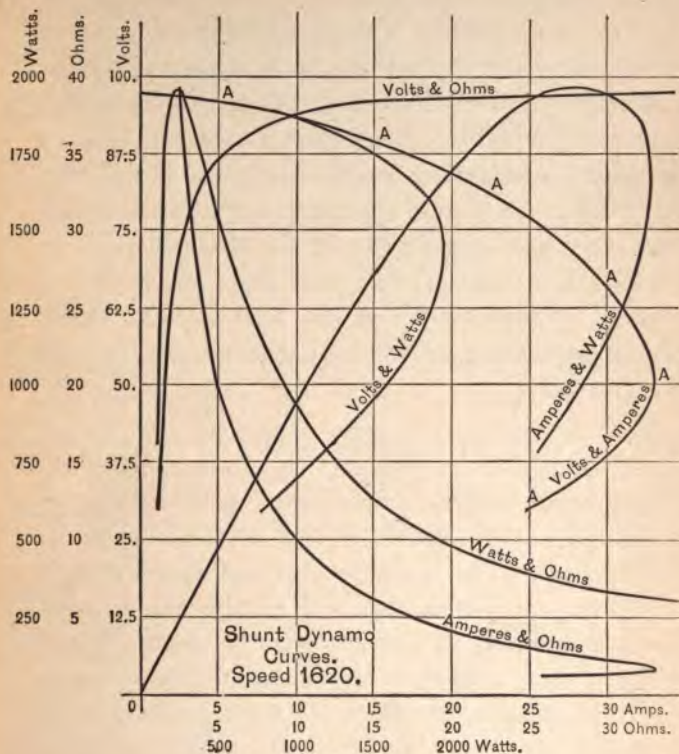


FIG. 45.

cuit. As the potential diminishes the current in the field coils also diminishes, and as a consequence there is a further reduction in the potential. Finally, when

the machine is short-circuited, there is practically no current at all in the field, and the potential difference is due to residual magnetism.

The characteristic of a compound-wound dynamo approximates a horizontal line more closely than that of a shunt dynamo. This is due to the fact that the increase in current in the series coil tends to counter-balance the diminution in effect of the shunt coil. However, the curve will ultimately bend down similar to the curve of a series dynamo, and this effect is due to the same causes—saturation of field and armature reaction. The character of the curve will be in a measure governed by the proportions of the shunt and the series fields.

#### SATURATION CURVE.

The saturation curve of a dynamo depends, not upon the windings of the machine, but upon its magnetic circuit. Indeed, the measurement of the potential is merely for convenience, and the results can be considered exactly as though they were magnetometer readings. If the speed is constant, and this is a very desirable condition, the potential difference is directly proportional to the induction in the armature. It is therefore evident that the saturation curves of series, shunt, and compound-wound machines are identical in form. In making the observations the dynamo should run at a constant speed, the fields should be sepa-

rately excited, and there should be no current in the armature. In case the speed cannot be relied upon to be constant, it should be measured at the time of each observation, and the reading corrected for the variation. This correction is based on the fact that with a constant induction the potential of an armature is directly proportional to the speed. If  $r$  is the normal speed of the dynamo and  $r_1$  the speed at the time of an observation,

$$E = \frac{r}{r_1} E_1;$$

where  $E_1$  is the measured, and  $E$  the corrected, potential difference.

The general form of the curve is shown in Fig. 46. The curve rises very rapidly at first and then the slope becomes more gradual, tending toward a horizontal line. The so-called point of saturation  $A$  is situated on the bend of the curve. A compound-wound dynamo should work below this point, on the straight portion of the curve, in order to obtain the best action of the series coil, while with a series or shunt dynamo it is desirable to work either at this point or slightly beyond it. The selection of co-ordinates will depend upon the purpose for which the test is made. Amperes in field or ampere turns are generally plotted as abscissæ and volts as ordinates. If it is desired to plot the induction through the

## 176 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

armature as ordinates, the values may be calculated from the potential difference, writing

$$\beta = \frac{10^9}{.167rC} E;$$

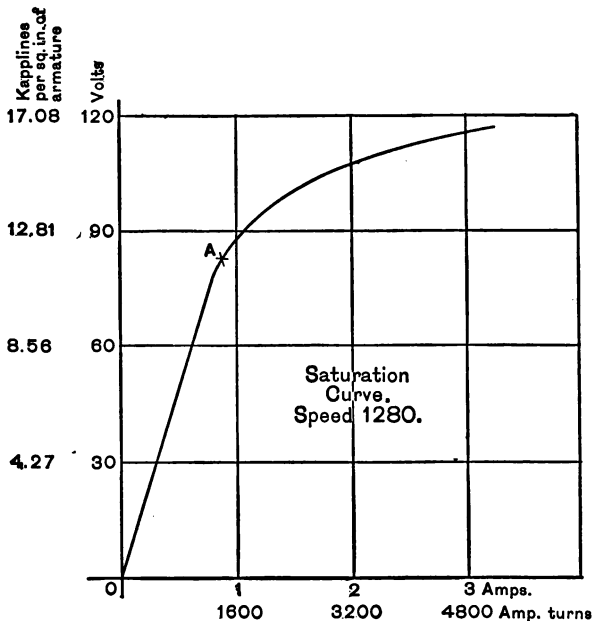


FIG. 46.

if it is desired to express the induction in Kapp

1,

$$\beta = \frac{10^9}{rC} E.$$

The induction per square inch or per square centimeter is sometimes adopted.

### SPEED CURVE.

In taking the speed curve of a dynamo, Fig. 47, the

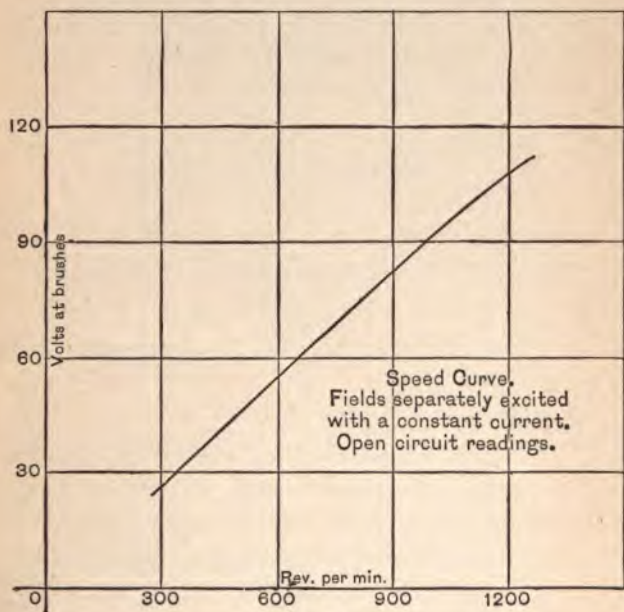


FIG. 47.

field magnets are separately excited with their normal working current, and the speed of armature gradually increased from zero to the normal speed of the ma-

chine. In making the test there should be no load upon the armature. Owing to the fact that an ordinary voltmeter will not indicate exceedingly low potentials, the curve appears to start a little to the right of the origin. The curve is sometimes taken with other than the normal working current in the field. In case of a shunt dynamo, if the field current is supplied by the dynamo itself, the curve starts at the lowest speed of self-excitation.

#### POTENTIAL CURVE.

The potential curve of a dynamo is shown in Fig. 48. There are two methods of making the observations for this curve. In one, a small brush is mounted on an arm in such a manner that it will press against the commutator. This arm is then set at different angles and the potential difference between the small brush and the brush of the machine is measured by means of a voltmeter. In plotting the curve the angles through which the small brush has advanced are plotted as abscissæ, and the potential differences between this brush and the brush of the machine as ordinates.

Another method of making the observations is to  
 t a second brush on the arm so that the distance  
 the two brushes will be the width of one seg-  
 the commutator. The potential difference

between the two brushes will be that generated by one coil of the armature at the angle of advance indicated

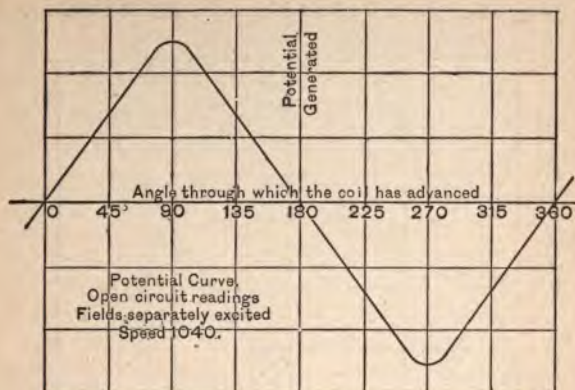


FIG. 48.

by the arm. This curve may be taken with no load on the machine or with any desired load.

#### LOSS IN ARMATURE CORE.

A point of considerable importance is the power lost in the core of the armature. It is important that the friction loss should not be charged against the core. Measure the power required to drive the armature at its normal speed with no current in the field. Then excite the fields by different currents, and measure the power required to drive the armature under the new conditions. The power required to drive the armature with a current in the field minus that required to drive it with no current in the field is the

power lost in the core for that current. The results may be plotted, Fig. 49, with current in the field as abscissæ, and watts loss in the core as ordinates.

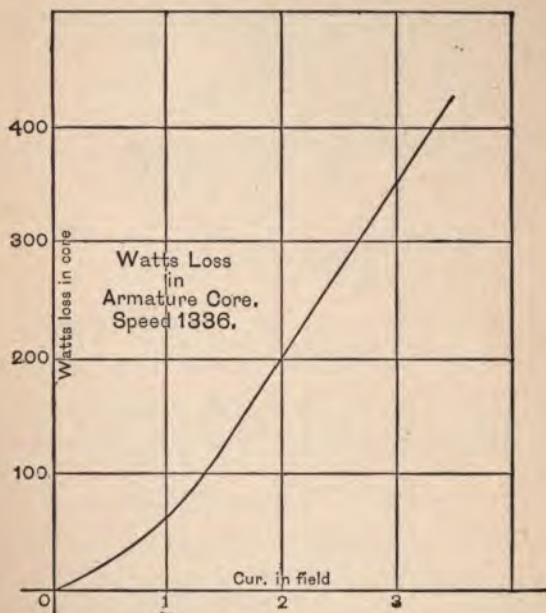


FIG. 49.

The speed should be constant throughout the test, and there should be no current in the armature. If a curve is taken after the armature is wound, the loss due to Foucault currents in the armature conductors is added to the losses. Therefore, if possible, make the test both before and after winding the armature. The

difference between the two curves will represent the power lost by foucault currents in the wire.

### HEATING OF THE ARMATURE.

One immediate effect of the energy lost in the core is an increase in the temperature of the armature. The ends and middle of the armature do not heat up equally, as is shown in the curves, Fig. 50. It is cus-

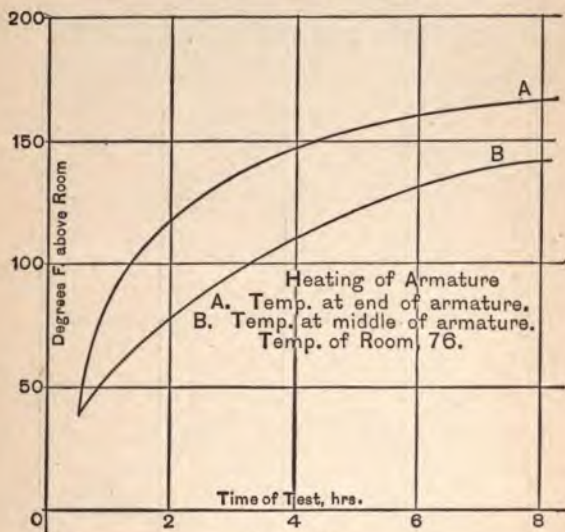


FIG. 50.

tomary to plot temperature in degrees above the room as ordinates, and length of run as abscissæ. Increase of temperature per unit of radiating surface is sometimes plotted as ordinates.

## 2 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

This curve may be combined with the one for power at in the armature, plotting watts loss per unit of cooling surfaces as abscissæ, and increase in temperature as ordinates. Evidently the curve may be plotted for different loads upon the armature, and various interesting combinations may be effected.

### MOTOR CURVES.

While the preceding curves may be taken from either a motor or a dynamo, there are a few curves

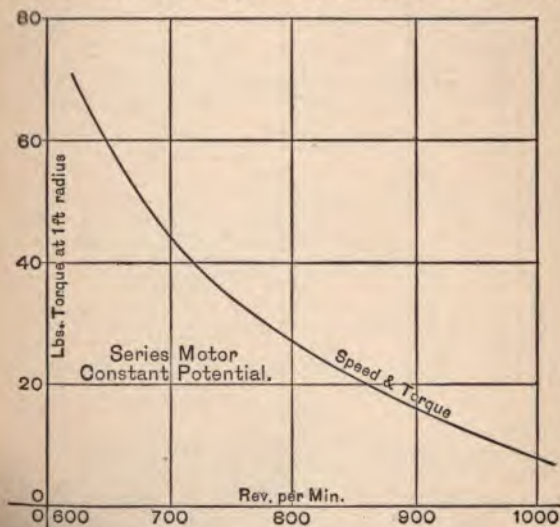


FIG. 51.

are essentially motor curves. One of the most important of these curves is the curve of speed and

torque shown in Fig. 51. The measurement of torque may be made by means of an absorption dynamometer, or—if it is more convenient to measure the horse-power—the torque, in pounds at one foot radius, may be calculated from the equation

$$T = \frac{33,000}{2\pi r} \text{ H. P.}$$

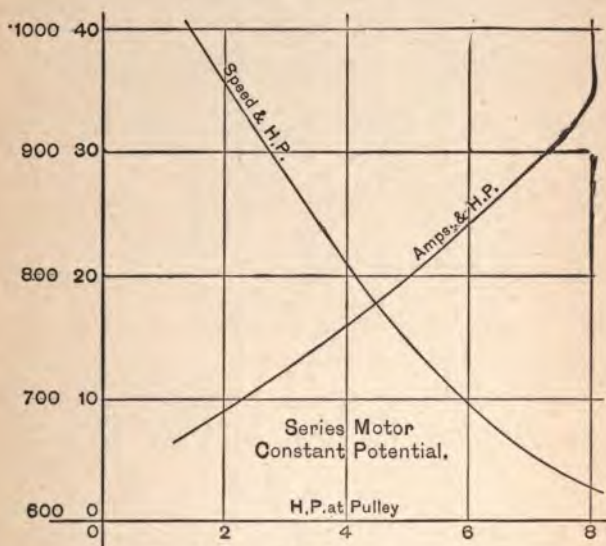


FIG. 52.

From the same set of observations the curve of amperes and horse-power, and of speed and horse-power, Fig. 52, may be plotted. In the case of a series

motor on a constant-current circuit, the curve representing the relation between amperes and horse-power should be replaced by one showing the relation between potential difference and horse-power. Curves may also be plotted for amperes and speed and am-

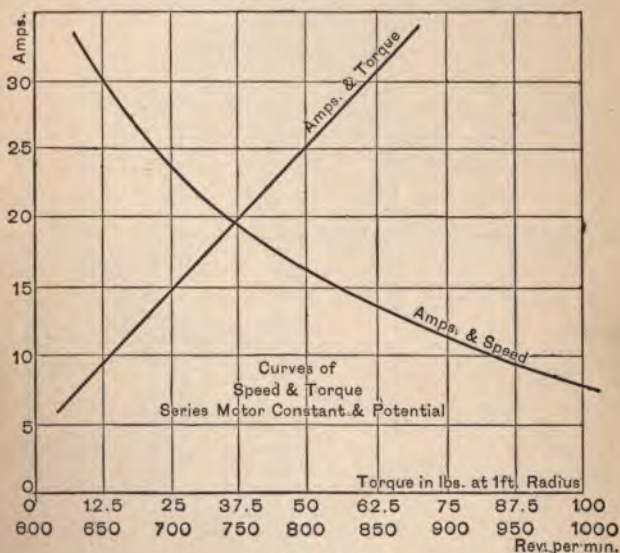


FIG. 53.

peres and torque (see Fig. 53). The curves shown are principally for a series motor on a constant-potential circuit. A similar set may be plotted for shunt and compound-wound motors. If the circuit is a constant-current one, the potential difference over the machine *is* the place of the current flowing.

## CHAPTER XII.

### EFFICIENCY TESTS.

THE commercial efficiency of a dynamo or motor is the ratio of the useful energy developed by the machine to the total energy it absorbs. In determining this ratio it is necessary to measure the electrical energy absorbed by a motor or developed by a dynamo, and the mechanical energy developed by a motor or absorbed by a dynamo. The measurement of the electrical energy is effected by means of a voltmeter and an ammeter, and has already been discussed. Therefore it will be necessary to consider only the principles of dynamometers for measuring mechanical energy. The dynamometer most generally used for measuring the output of a motor is the absorption dynamometer or Prony brake shown in Fig. 54.

The pulley in slipping between the two parts *m* and *p* encounters a resistance which depends upon the pressure between the face of the pulley and the pieces *m* and *p*. This pressure is adjusted by the nuts *a a*.

If  $W$  is the weight required at the end of the beam to balance it and  $L$  the distance, in feet, between the centre of the pulley and the point of application of the

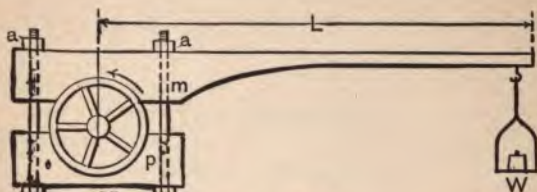


FIG. 54.

weight, the force acting at the face of the pulley is  $LW$  pounds.

The displacement is evidently  $\frac{\pi rd}{12}$  feet per minute, where  $d$  is the diameter of the pulley in inches and  $r$  the revolutions per minute. Therefore the power absorbed is

$$\text{H. P.} = \frac{\pi rdLW}{12 \times 33,000} = \frac{rdLW}{126,050}.$$

Since this dynamometer absorbs the power it measures, it cannot be used for measuring the power delivered to a dynamo. For this purpose a transmission dynamometer is necessary. A well-known dynamometer of this class is shown in Fig. 55. Two shafts,  $mm$ , carrying idle pulleys,  $oo$ , rest upon fixed supports,  $aa$ . Upon the same shaft as pulley  $d$  is a pulley connected to the source of power, and a pulley on

the same shaft as pulley *c* is belted to the dynamo. An endless belt, *neghbn*, connects the pulleys *d*, *o*, *o*, and *c*. It is evident that if the knife-edges *aa* are in line with the belt, the strains on the parts of the belt marked *e* and *b* will have no influence on the frames

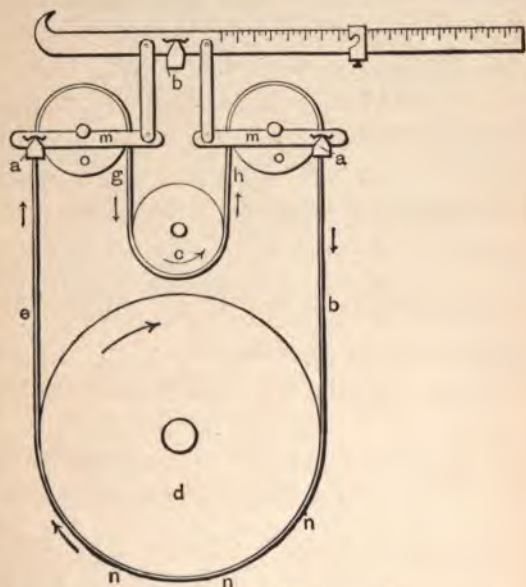


FIG. 55.

*mm*, but that the difference in tension on the parts marked *g* and *h* will be registered upon the beam. The reading of the beam is therefore proportional to the difference in tension between the two sides of the belt,

and when multiplied by the dynamometer constant gives the value of the torque. Nearly all transmission dynamometers measure the difference in tension between the two sides of the belt, and a description of the different types is unnecessary.

A method of measurement introduced by Prof. Brackett may be used for either dynamos or motors. It consists in mounting the machine to be tested upon a cradle which rests on knife-edges. Care must be taken that the centre of rotation is in line with the knife-edges, that the belt from the machine is vertical, and that the cradle is carefully balanced upon the knife-edges after the machine has been fastened down and before it is started. This balancing is effected by securing weights to different parts of the cradle, and is necessary since, if the cradle is not in its normal position before starting, the force required to bring it into position will be charged to the machine being tested. A horizontal arm perpendicular to the line of knife-edges acts as a scale-beam, the readings being directly proportional to the torque. Since the dynamometer measures the turning moment of the cradle, it is evident that the dynamometer may be used for either dynamo or motor testing. However, when testing a motor it will be necessary to provide some machine for absorbing the energy developed, for the dynamometer merely measures the energy, but does not absorb any of it. It very often occurs that a dy-

namometer for measuring mechanical energy cannot be obtained. Even under these circumstances an accurate efficiency test may be made, the only instruments necessary being an ammeter, a voltmeter, and a speed-indicator. In following this method the losses in the machine are first determined. These losses added to the output of a dynamo give the power applied at the pulley. If subtracted from the electrical energy delivered to a motor, the result is the power available at the pulley. The loss in either a dynamo or a motor may be divided into wire loss, iron loss, and friction loss. Of these the wire loss will depend upon the current flowing, but the other losses (iron and friction) may be considered constant for the same speed. In the determination of these losses the machine is run as a motor with the belt removed. It is evident that all the power delivered to the machine is waste, since no useful work is performed.

Consider the case of a shunt motor, the law being equally true for a series machine. Let  $C_a$  represent the armature current when the motor is running empty,  $R_a$  the armature resistance,  $C_s$  the field current, and  $R_s$  the field resistance. The wire loss is

$$C_a^2 R_a + C_s^2 R_s.$$

The total power expended is

$$(C_a + C_s)E,$$

## 190 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

where  $E$  is the potential difference of the mains. Then there are

$$(C_a + C_s)E - C_a^2 R_a - C_s^2 R_s$$

watts not accounted for. This loss is due to foucault currents, hysteresis, and friction, and may be considered constant for the same speed. The motor should now be caused to run at different speeds by varying the strength of field, and this loss determined for each speed. If the speed of the motor is varied by means of a rheostat, care must be taken to subtract the loss in the rheostat. The losses due to foucault currents, hysteresis, and friction having been determined for different speeds, the curve  $A$ , Fig. 56, may be plotted. Revolutions per minute are plotted as abscissæ, and watts loss as ordinates. Representing this loss by  $K$ , we may write for the power available at the motor pulley

$$\text{H. P.} = \frac{EC - \{C_a^2 R_a + C_s^2 R_s + K\}}{746}.$$

The commercial efficiency of the motor is

$$\eta = \frac{EC - \{C_a^2 R_a + C_s^2 R_s + K\}}{EC}.$$

If the machine is operating as a dynamo, the power applied to the pulley is

$$\text{H. P.} = \frac{EC + \{C_a^2 R_a + C_s^2 R_s + K\}}{746}.$$

The commercial efficiency is

$$\eta = \frac{EC}{EC + \{C_a^2 R_a + C_s^2 R_s + K\}}.$$

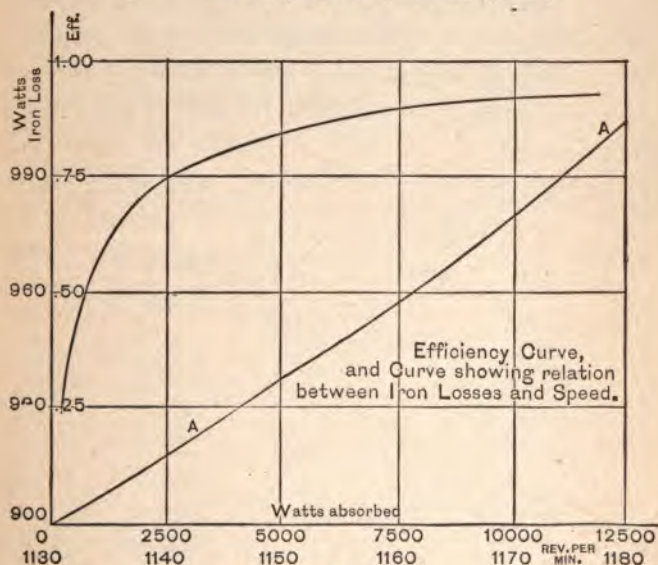


FIG. 56.

If the machine is now run at different loads, the efficiency curve, Fig. 56, may be plotted. The value

## 192 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

of  $K$  being taken from the curve  $A$ , Fig. 56, it must be remembered that if the speed of the machine changes, the value of  $K$  must be changed to correspond.

The following test of a compound-wound dynamo may prove of interest in this connection.

The machine was run at a constant load and measurements of current and potential taken. The losses were calculated by the method just described. Indicator cards were taken from the engine at intervals during the test. At the completion of the test the belt was run off the machine and several cards taken to determine the power lost in friction of the engine, shafting, etc.

Mean current in line.....	135 amp.
“ “ “ field.....	1.7 “
“ “ “ arm.....	136.7 “
“ potential at brushes.....	240.5 volts.
“ “ over series coil.....	.734 “
Speed .....	934 rev. per min.
Electrical H. P.....	43.5
Indicated H. P. absorbed in friction.	17.6
Total indicated H. P.....	66.4
Indicated H. P. at dynamo.....	48.8
Efficiency.....	.893

Running as a motor:

Line current.....	11.9 amp.
Field “ .....	1.63 “

# CONTINUOUS-CURRENT DYNAMOS AND MOTORS. 193

Armature current.....	10.27 amp.
Potential at brushes.....	230 volts.
“ over series coil.....	0.5 “
Speed.....	935 rev. per min.
Armature resistance.....	.025 ohms.
Field “ .....	141 “
Total loss in motor.....	2740 watts.
Wire loss in armature.....	2.64 “
“ “ “ field.....	374.9 “
“ “ “ series coil.....	.6 “
Total wire loss.....	378.14 “
Loss due to foucault cur., hysteresis, and friction..	} 2362 “

Having determined this constant loss, let us return to the results observed in the test :

Wire loss in armature.....	468 watts.
“ “ “ series coil.....	99 “
“ “ “ shunt field.....	408 “
Constant loss due to foc. { cur., hyster., and friction }	2362 “
Total loss.....	3337 “

Since the output is 135 amperes at 240.5 volts,

Watts output.....	= 32,400
“ loss.....	= 3,337
“ absorbed.....	= 35,737
Efficiency.....	= .907

This result, 90.7%, as compared with 89.3% shown by the indicator, proves that there is no error introduced in assuming the value of  $K$  constant, for a variation of 1% is liable to occur from error in observation.

The error is no more likely to be in the electrical method than in the indicator method.

Although it is not necessary to divide the factor  $K$ , it is sometimes desired to do so in order to find the effect of certain changes. The factor is made up of friction, foucault currents, and hysteresis. The first step in the separation is to determine the friction. This is done by opening the field circuit of the machine and driving the armature at different speeds by means of a motor whose efficiency curve is known. Representing the power expended in friction by  $x$ , the loss due to foucault currents and hysteresis is  $K - x$ . Now run the dynamo at two different speeds and determine the value of  $K - x$  for each speed. Represent this loss at the speed  $r$  by  $a$ , and at the speed  $r_1$  by  $b$ . Since foucault currents are electric currents in the iron, both their potential difference and current will increase with the speed, and the loss is proportional to the square of the speed. Hysteresis depends directly on the speed, and therefore we may write

$$mr + nr^2 = a, \quad . \quad . \quad . \quad . \quad . \quad (A)$$

$m$  and  $n$  are constants to be determined. We so write

$$mr_1 + nr_1^2 = b. \quad . \quad . \quad . \quad . \quad . \quad (B)$$

Multiplying (B) by  $\frac{r}{r_1}$  and subtracting from (A),

$$n(r^2 - rr_1) = a - \frac{br}{r_1};$$

$$n = \frac{ar_1 - br}{r_1 r^2 - rr_1^2}.$$

Multiplying (B) by  $\frac{r^2}{r_1^2}$  and subtracting from (A),

$$m\left(r - \frac{r^2}{r_1}\right) = a - \frac{br^2}{r_1^2};$$

$$m = \frac{ar_1^2 - br^2}{rr_1^2 - r_1 r^2}.$$

Therefore at a speed  $r$  the value of the foucault-current loss is

$$nr^2 = \frac{ar_1 - br}{r_1 r^2 - rr_1^2} r^2 = \frac{arr_1 - br^2}{r_1 r - r_1^2}.$$

The loss due to hysteresis is

$$mr = \frac{ar_1^2 - br^2}{rr_1^2 - r_1 r^2} r = \frac{ar_1^2 - br^2}{r_1^2 - rr_1}.$$

It is important in this determination that the value of  $\beta$  should be the same in each set of observations.

## 196 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

If the potential difference is measured at the brushes at the different speeds, just before taking the readings, the fields should be so adjusted that

$$\frac{E}{E_1} = \frac{r}{r_1},$$

where  $E$  is the potential difference at the speed  $r$ , and  $E_1$  that at the speed  $r_1$ . When this equation is satisfied the value of  $\beta$  is the same in each case.

## CHAPTER XIII.

### INDICATOR-DIAGRAMS.

IN considering the subject of the steam-engine indicator we will assume a knowledge of the various parts of the instrument and of the method of taking an indicator-card. These are matters in which the engineer should receive personal instruction; and since they depend in a measure on the particular instrument used, no general treatment is possible. A few general notes may, however, be given on the attachment of the indicator and the proper adjustment of the drum motion. All modern engines have their cylinders tapped for the indicator-pipes, and it is only necessary to avoid cramping the steam in its passage from the cylinder to the indicator. As a general rule the pipes from the two ends of the cylinder are brought to a three-way cock situated near the middle of the cylinder. It is desirable that all elbows in the pipe should be of large radius, although the same effect is sometimes gained by using the elbow of a larger size of pipe.

Indeed, some engineers advocate the use of two indicators, one attached directly at each end of the cylinder. Under ordinary circumstances this practice is unnecessary, and seldom resorted to unless the length of stroke is very great.

If the cylinder is not tapped for the indicator-pipes, great care should be exercised in locating the holes. The cylinder-head is removed and the engine turned to a centre with the piston at the head end\* of the cylinder. The cylinder is now drilled and tapped so that the hole is beyond the end of the piston. Care must be taken that the piston does not cover any part of the hole, in order that the steam may have a free passage. Carefully clean the chips from the cylinder and replace the cylinder-head. Be sure that the cylinder-head does not cover any part of the hole, chipping away a portion of the head if necessary. In drilling the crank end of the cylinder use every precaution to avoid getting chips in the cylinder, as it is generally inconvenient to remove the piston in order to clean out the cylinder. If steam (though not at full pressure) is turned into this end of the cylinder, it will tend to blow out the chips as they are cut, and though slightly inconvenient to the workman it saves the lining of the cylinder to a great extent. A magnetized drill and tap will also be found of value in preventing

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\* The end of the cylinder toward the crank or fly-wheel is called the crank end, and the other end the head end.

the chips from falling into the cylinder. Under any circumstances it is well to allow steam to blow through the cylinder after tapping, in order to remove any foreign substance which may have fallen in. In some engines it is necessary to drill the holes in the cylinder-heads, and as this necessitates another bend in the pipe, large elbows are particularly necessary in these cases.

The most important point to be considered in obtaining the drum motion is the ratio of this motion to the stroke of the engine. This ratio must be constant, and if a pantograph cannot be obtained, any substitution must be very carefully considered before it is adopted. A very common substitute for the pan-

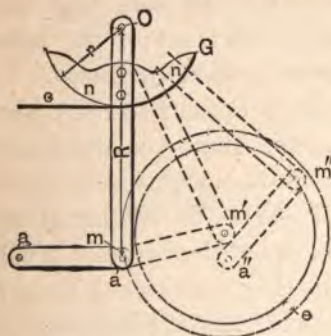


FIG. 57.

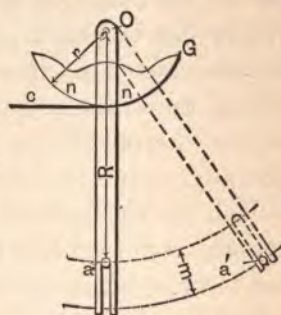


FIG. 58.

tograph is the pendulum, two forms of which are shown in Figs. 57 and 58. Neither form should be used unless the length  $R$  is very great compared to the

stroke of the engine. In Fig. 57  $Om$  is a bar pivoted at  $O$  and connected by a short rod,  $am$ , to the cross-head of the engine. The point  $O$  is so chosen that when the engine has completed exactly one half the stroke, the rod  $Om$  is vertical and the rod  $am$  is horizontal. A segment of a circle,  $nn$ , is rigidly attached to the rod  $am$ . The indicator-cord passes along the circumference of the circle and is secured at  $G$ . It is evident that the movement of the cord (and consequently of the indicator-drum) bears a fixed ratio to the movement of the point  $m$ . Therefore, in order that the reduction of motion may be constant, it is necessary that the motion of the point  $a$  (or the cross-head) should bear a constant ratio to the motion of the point  $m$ . Let the piston move forward until the point  $a$  takes the position  $a'$ , and  $m$  becomes  $m'$ . Let it advance again until  $a$  becomes  $a''$  and  $m$  becomes  $m''$ . Let the motion of the piston in each case be the same, that is,  $aa' = a'a''$ . Represent this distance by  $d$ .

Let the reduction of motion be in the ratio  $\frac{r}{R}$ , then the movement of the drum for a movement  $d$  of the piston is  $\frac{dr}{R}$ ; and since the two movements of the piston are of the same magnitude, the two values of  $\frac{dr}{R}$  should be the same. That is, since in the same circle equal chords subtend equal arcs, a circle

drawn with the centre at  $m'$  and a radius  $am$  should pass through the point  $m''$  as well as the point  $m$ . That this is not true is evident. When the distance  $R$  is very great compared to the stroke of the engine, the angle through which the rod  $Om$  moves is very small, and this combination should be used only when the value  $e$  is so small that it may be neglected.

In Fig. 58 the horizontal rod has been omitted and a slot cut in the end of the vertical rod. This slot works over a pin  $a$  in the cross-head. The method of taking the cord from the segment of a circle is retained. The reduction of motion is  $\frac{r}{R}$  at the middle of the stroke and  $\frac{r}{R+m}$  when the piston has advanced the distance  $aa'$ , and in order to follow this plan of reducing the motion it is necessary that the value of  $m$  be so small that it may be neglected without sensible error.

Let us now examine the different lines of the diagram. Some students find the reading of indicator-cards rather difficult, because they have fixed upon certain general forms as having definite meanings. This method of reading diagrams should be avoided. To correctly read a card it must be remembered that the diagram represents merely the pressure of the steam in the cylinder at the different portions of the stroke. The diagram does not tell the cause of

## 202 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

the variation in pressure, but *does* correctly indicate the pressure of the steam in the cylinder; leaving the engineer to draw his own conclusions in regard to the cause and remedy.

In the diagram, Fig. 59, the pressure of the steam in the cylinder is proportional to the length  $AF$  at the

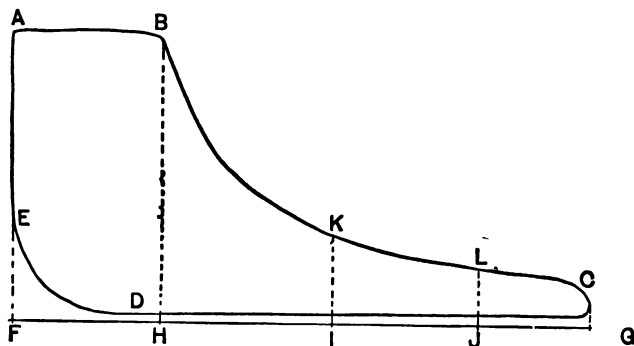


FIG. 59.

beginning of the stroke. Steam is freely admitted to the cylinder until the piston has completed about one fourth of the stroke. During this portion of the stroke the pressure remains constant. Then, at  $B$ , the valve closes and no more steam is admitted to the cylinder. The steam in the cylinder now expands, increasing in volume and diminishing in pressure until the forward stroke is completed, when at  $C$  the exhaust valve opens and the steam escapes from the cylinder. The

exhaust valve remains open until the piston has nearly completed the return stroke. Then at *D* the exhaust valve closes and the steam remaining in the cylinder is compressed, its pressure increasing for the remainder of the stroke, when the admission valve opens and the steam pressure immediately rises to the initial pressure. The diagram may be subdivided into

- AB*, the steam line ;
- BC*, the expansion line ;
- CD*, the exhaust line ;
- DE*, the compression line ;
- EA*, the admission line ;
- FG*, the atmosphere line.

This last line, *FG*, is drawn with no steam in the indicator, and the distance from this line of any point in the curve represents the pressure (above the atmosphere) of the steam at that portion of the stroke. It must be remembered that only one end of the cylinder has been considered, and that the action of the other end is similar, except that the return stroke of one end is the forward stroke of the other. Therefore, in order to truly represent the condition and working of an engine, it is necessary to draw a pair of diagrams as shown in Fig. 60, where the diagrams *H* and *C* are taken from the head end and crank end of the cylinder. The two diagrams should be practically the same.

## 204 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

As nothing is to be gained by the repetition of a curve, advantage has been taken of the two diagrams to show two entirely different valve-settings on the same card.

Examining the diagram, Fig. 60, for the head end of the cylinder, we notice that the steam, expansion,

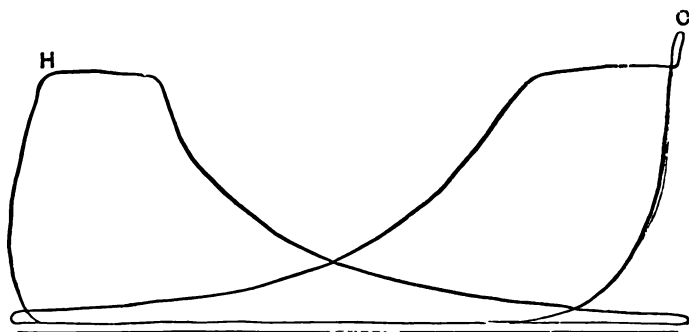


FIG. 60.

and exhaust lines are quite satisfactory. We also notice that the exhaust closes a little late, and consequently there is not so much compression as could be desired. This may be remedied by closing the exhaust a little earlier. But the principal trouble is in the admission line, which leans to the right instead of being vertical. That is, the piston has completed a considerable portion of the return stroke before the steam attains the normal pressure. It is evident that the steam cannot enter the cylinder fast enough.

This may be due to the admission valve opening too late, or to the ports not being of sufficient size. The steam line being horizontal indicates that, when reached, the pressure is well maintained. Therefore it is reasonable to assume that the ports are of sufficient size, and the trouble lies in a late opening of the valve. Since the exhaust closes late there is little compression, and further, as the piston is starting back when the valve opens, the volume to be filled is constantly increasing, and it is consequently some time before the full pressure is attained. If the exhaust closes later there will be more compression, and an earlier opening of the admission valve will insure better working. The diagram, Fig. 60, for the crank end shows the effect of closing the exhaust valve too early. The compression is so great that the steam in the cylinder attains a higher pressure than the initial, and when the admission valve opens steam actually escapes from the cylinder until the pressure reduces to the initial. The remedy is evidently to close the exhaust later.

The head-end diagram, Fig. 61, shows the effect of admitting steam to the cylinder too soon. After the exhaust has closed there is about the proper amount of compression; then the valve opens and steam at full pressure is admitted for the remainder of the stroke. This practice is not only the reverse of economy, but it also subjects the engine to

severe strains which it was never intended to withstand, and will eventually cause trouble. The valve-setting must be changed and steam not admitted until the end of the stroke. As the compression curve was

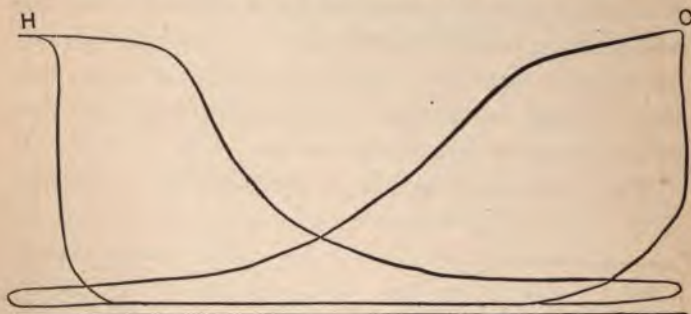


FIG. 61.

satisfactory, the relative actions of the exhaust and admission valves were correct, and it will be necessary to delay the closing of the exhaust as well as the opening of the admission valve. If this is not done there will be too much compression, and a diagram similar to the crank-end diagram Fig. 60 may be expected. In the crank-end diagram Fig. 61 the initial pressure is not maintained. This is evidence of the steam being cramped in admission, and may be due to long, hooked, or small pipes, or to small ports. This class of diagrams is often taken from engines having throttle

10RS.

he head-end diagram, Fig. 62, it is almost im-

possible to tell just where the valve closes. The steam line is horizontal and indicates a sufficient supply of steam at the beginning of the stroke. Diagrams of this class are taken from all types of engines, particularly where they have not been properly cared for and are indicative of leaky valves. The point of cut-off is not at all clearly defined, and the expansion line is very poor, due to steam leaking into the cylinder after the valve has closed.

The crank-end diagram, Fig. 62, indicates that the

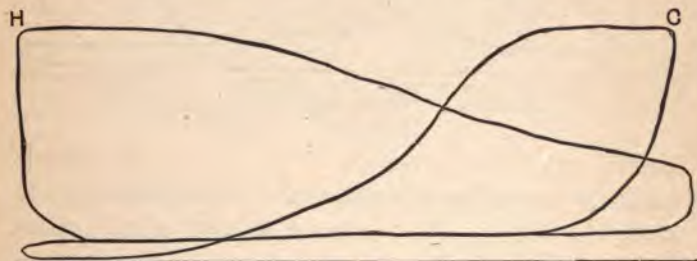


FIG. 62.

exhaust is cramped. The steam in the cylinder expands to so low a pressure that when the exhaust valve opens, instead of steam escaping from the cylinder, air rushes in. The remedy is to enlarge or shorten the exhaust pipes. There would be no objection in this diagram to open the exhaust at the beginning of the loop.

Diagrams Figs. 63 and 64 were taken from high-

speed engines with normal and light loads respectively. It will be noticed that the lines are more irregular than those which have heretofore been considered.

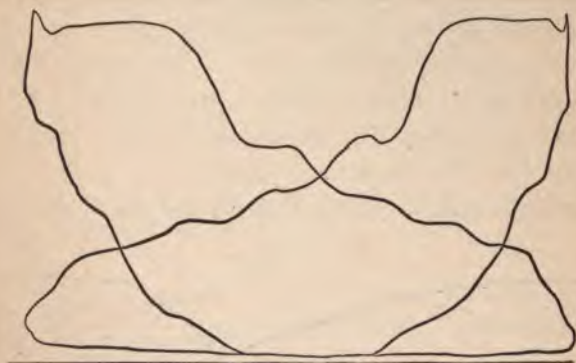


FIG. 63.

This is a common characteristic of diagrams from high-speed engines, and is due in a large measure to the spring of the indicator not being able to quickly accommodate itself to marked changes in load. It can be avoided a great deal by the use of a heavy spring and short drum motion.

The diagrams treated have all been taken from condensing engines. Fig. 65 shows a pair of diagrams from a condensing engine. The most noticeable difference between these diagrams and those from a non-condensing engine is that the exhaust line is not at the atmosphere line *om*. If, however, a line

*AB* is drawn at a distance below the atmosphere line corresponding to a pressure of 14.7 lbs., the curves may be transferred to the new axes, and will exhibit all the characteristics of diagrams from non-condens-



FIG. 64.

ing engines. The line *AB* is known as the vacuum line, and is taken as the zero of pressure. The pressures indicated by the diagrams are now the pressures above a vacuum and not above the atmosphere. Another feature of the diagram Fig. 65 is that there is little or no compression. This must be taken as a characteristic, not of condensing engines in general, but of this particular case. In compound engines it is only necessary to consider the two cylinders as two distinct engines, and to indicate them both at the same time.

The few diagrams which have been discussed are

characteristic of the troubles most generally encountered. Various combinations and modifications of them will be met with, but they should offer no particular difficulty to the student.

It is sometimes desirable to plot the theoretical

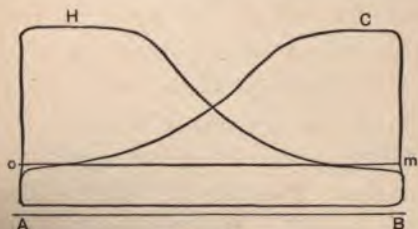


FIG. 65.

a curve of an engine and compare it with the  
 own by the indicator. It is known that if any  
 of steam is allowed to expand, the product of  
 the and pressure is constant. Therefore, if we  
 measure the volume and pressure of the steam in  
 the cylinder of an engine at any portion of the stroke,  
 after the admission valve has closed and before the  
 exhaust valve has opened, the theoretical expansion curve  
 can be constructed. The indicator measures the  
 pressure of the steam, and it is therefore only neces-  
 sary to measure the volume. In order to determine  
 the volume necessary to know the volume of steam  
 in the cylinder at the end of the piston and the cylinder-head.  
 This is measured in the following manner: Turn

the engine upon a centre. Remove the indicator and fill the space between the end of the piston and the cylinder-head with water. This water should be taken from a vessel of water which has previously been weighed. Now weigh the water remaining in the vessel. This weight subtracted from the original weight gives the weight of water in the cylinder. Knowing the weight of a cubic foot of water, the volume of the clearance space is quickly calculated. The volume of the clearance divided by the area of the piston gives the length of stroke corresponding to clearance. This length can be measured directly if it is desired. Having weighed the amount of water which can be poured into the cylinder when the engine is on a centre, make a mark on the guide indicating the position of the cross-head. Now weigh out just exactly as much water as is in the cylinder, and turn the engine forward until this amount can just be added to the amount already in the cylinder. Make a second mark on the guide indicating the new position of the cross-head. The distance between the two marks is the length of stroke corresponding to clearance.

In making these measurements it is absolutely necessary that all the valves should be closed. The clearance should be determined for each end of the cylinder.

Consider the diagram Fig. 66. Having measured

the length of stroke corresponding to clearance, drop a perpendicular from the end of the diagram and lay off from the intersection with the atmosphere line the distance  $d$ . This length,  $d$ , must bear the same ratio to the length of the diagram that the length of stroke

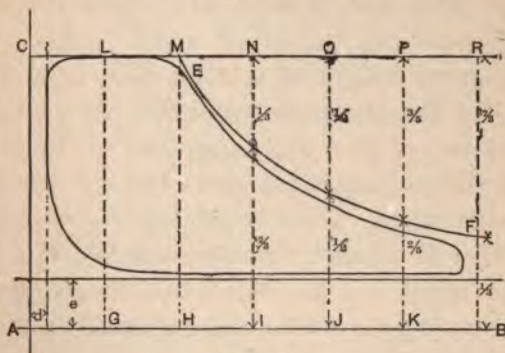


FIG. 66.

corresponding to clearance bears to the length of stroke. Draw the line  $CA$ . This line represents the zero of volume. Now draw the vacuum line  $AB$  parallel to the atmosphere line and at a distance  $e$  ( $= 14.7$  lbs.) below it.

This line represents the zero of pressure. The intersection  $A$  of the lines  $AC$  and  $AB$  is evidently the origin of both pressure and volume, and the lines themselves are the axes of the expansion curve. Now draw a series of lines  $GL$ ,  $HM$ ,  $IN$ ,  $JO$ ,  $KP$ , etc., parallel to the atmosphere line and let the distances between them be equal.

The curve may be drawn from any point on the expansion curve, but it is customary to select either the point of cut-off (where the admission valve closes) or the point of release (where the exhaust valve opens). Selecting the point of cut-off, it is necessary that one of the parallel lines,  $HM$ , should pass through this point.

At the point of cut-off there is in the cylinder a volume of steam  $AH$  at a pressure  $HM$ . When the piston has advanced to  $I$  the volume has increased 50%; and since the volume has increased to  $\frac{3}{2}$ , the pressure must diminish to  $\frac{2}{3}$  of the original. At  $J$  the volume has doubled and the pressure become  $\frac{1}{2}$ . At  $K$  there is  $\frac{5}{2}$  the original volume and  $\frac{2}{5}$  the original pressure. In this manner any number of points on the expansion curve may be located.

Another method of constructing the theoretical expansion curve is preferred by many engineers. The lines  $ON$  and  $OM$ , Fig. 67, are the zero lines of volume and pressure respectively, and are located in the same manner as in the preceding construction. Extend the steam line  $EF$ , and draw a horizontal line  $NR$  any convenient distance above it. Draw a vertical line  $CD$  through the point of cut-off (or through the point of release if preferred), and from its point of intersection  $D$  with the line  $NR$  draw a straight line to the origin. At the point where this line intersects the line  $EF$  draw a vertical line  $AB$ . To determine a point

on the curve draw any line  $OG$  passing through the origin. From its intersection with the line  $NR$  draw a vertical line  $GH$ , and from its intersection with the

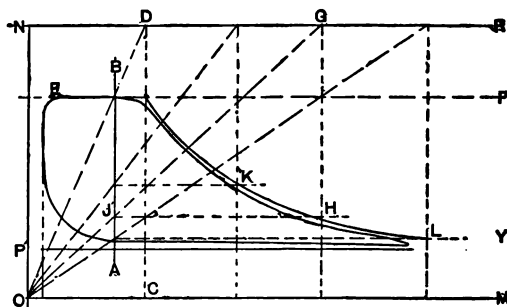


FIG. 67.

line  $AB$  draw a horizontal line  $JH$ . The intersection  $H$  of the lines  $GH$  and  $JH$  is a point on the curve. In this manner any desired number of points on the curve may be determined.

## CHAPTER XIV.

### STEAM-ENGINE CALCULATIONS.

ONE of the most common uses of the indicator-diagram is the determination of the amount of energy developed by the engine at the time of taking the card. In this calculation the diagram indicates merely the pressure acting on the piston. It has been explained that the height (above the atmosphere line) of a point on the curve is a measure of the pressure of steam in the cylinder at that part of the stroke. This pressure is not constant, but varies from the initial pressure to back pressure, as indicated by the exhaust line. The most accurate method of finding the average pressure per square inch is to divide the area of the diagram (measured by a planimeter) by its length, and multiplying the quotient by the scale of the indicator-spring. However, a planimeter is not always available, and other means must be used to determine this average pressure or M. E. P. (Mean

Effective Pressure). Probably the most satisfactory substitute for this method is to divide the length of the diagram into a number of equal parts, and at each division to erect perpendiculars to the atmosphere line. The average of the effective pressures \* measured on these lines will be the Mean Effective Pressure per square inch. Having now the average pressure on the piston, it is only necessary to determine the displacement in a given time in order to express the horse-power developed by the engine. Let  $D$  represent the diameter in inches of the piston,  $D_1$  the diameter of the piston-rod,  $L$  the length of stroke in feet,  $R$  the revolutions per minute, and  $P$  the mean effective pressure per square inch on the piston. Then it is evident that the displacement in one minute is  $2RL$  feet. The pressure against the piston from the head end of the cylinder is  $\frac{\pi D^2 P}{4}$  lbs., and from the crank end is  $\frac{\pi(D^2 - D_1^2)P}{4}$  lbs. Therefore, since each end acts but once in one revolution, the horse-power developed by the head end of the engine is

$$HP = \frac{\pi D^2 P R L}{4 \times 33,000}.$$

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\* In measuring the effective pressures at the different points from the atmosphere line, the back pressure must be deducted, as it performs no useful work.

The horse-power developed by the crank end is

$$HP = \frac{\pi(D^2 - D_1^2)PRL}{4 \times 33,000},$$

and the total power developed by the engine is

$$\begin{aligned} HP &= \frac{\pi D^2 PRL + \pi(D^2 - D_1^2)PRL}{4 \times 33,000} \\ &= \frac{\pi(2D^2 - D_1^2)RL}{4 \times 33,000} P. \end{aligned}$$

If a great many cards are to be taken from an engine, the calculations may be shortened by determining the engine constant. Assuming that the speed remains constant, the coefficient of  $P$  in the above expression is constant. This coefficient is the engine constant:

$$K = \frac{\pi(2D^2 - D_1^2)RL}{132,000}.$$

And once determined, the power expressed by an indicator-card is quickly calculated by multiplying this constant by the mean effective pressure measured by the card.

The horse-power measured by the indicator-card is not the power delivered by the engine to the dynamo or the line shaft, but includes the power required

to overcome the friction of the engine itself. It is therefore necessary to indicate the engine running empty, and to deduct the power absorbed from any observations taken during a test, provided the power sought is that delivered to the machines.

Before discussing other calculations which may be made from the indicator-diagram, it is advisable to consider some of the properties of saturated steam.

Conceive a vertical cylindrical vessel containing a quantity of water under a weighted piston. Assume the temperature of the water to be  $32^{\circ}$  F. If heat is now applied to the vessel, the temperature of the water increases, but its volume remains unaltered except for the slight expansion due to its increased temperature. At a temperature depending upon the weight on the piston the formation of steam commences. If the pressure upon the water is merely the pressure of the atmosphere, this temperature is  $212^{\circ}$  F. There is now no further increase in temperature until all the water contained in the vessel is converted into steam, but the volume is increased and the piston lifted. In effecting these changes a certain amount of heat has disappeared, and as heat is a form of energy it may be said that a certain amount of energy has been expended.

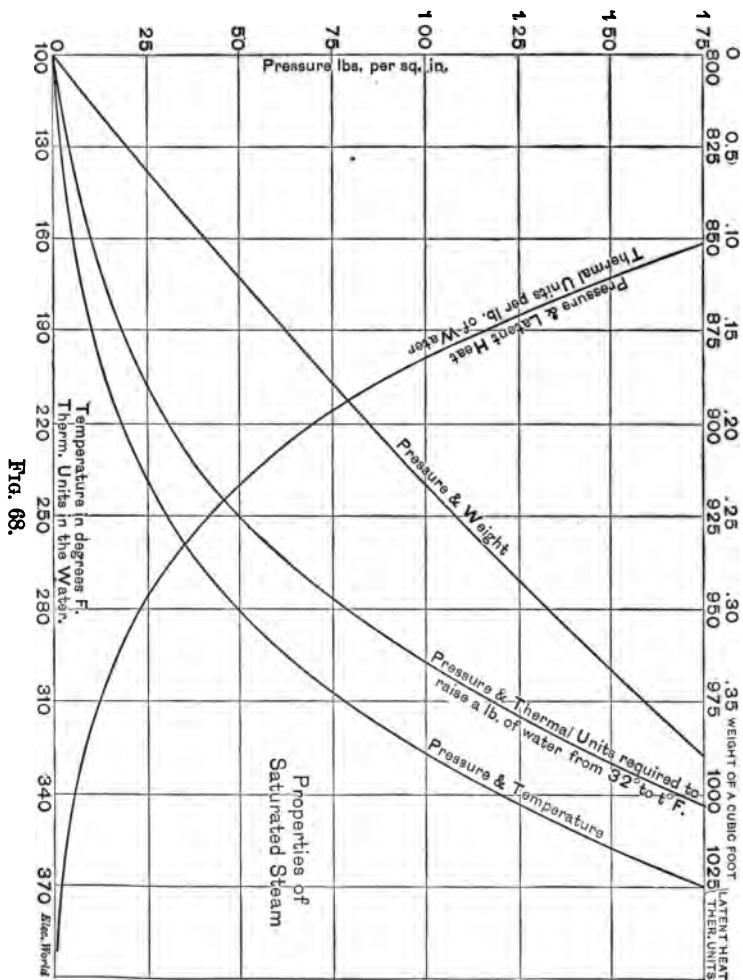
A thermal unit is the amount of heat required to raise one pound of water from  $39^{\circ}$  F. to  $40^{\circ}$  F., and is equivalent to 772 ft.-lbs. of work. It is customary for

practical engineers to consider this quantity as constant at all parts of the scale. This is not exact, however, as the energy required to raise a given weight of water one degree increases with the temperature.

The number of thermal units contained in a given volume of water at a definite temperature may be defined as the number of thermal units required to raise the temperature of the water from  $32^{\circ}$  F. to  $t^{\circ}$ . According to some practical writers on the subject, the number of thermal units contained in 1 lb. of water at a temperature of  $185^{\circ}$  F. is 153, while the number actually contained is 153.6, an error of .6 of a thermal unit or 463.2 ft.-lbs.

Now, having a pound of steam at a temperature of  $185^{\circ}$  F., we know that 153.6 thermal units have been expended in increasing the temperature of the water from which it was formed from  $32^{\circ}$  F. to  $185^{\circ}$  F. If the amount of heat applied to the vessel had been measured, it would have been found greatly in excess of 153.6 thermal units. The amount of heat required to convert a pound of water at a definite temperature into steam at the same temperature is known as the latent heat of evaporation, and if the temperature of the steam is  $185^{\circ}$  F. it amounts to 984.8 thermal units. The amount of heat required to raise a pound of water from  $32^{\circ}$  F. to a particular temperature and to convert it into steam at that tem-

## 220 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.



perature is the total heat of evaporation. Continuing the example for 185° F. it amounts to

$$153.6 + 984.8 = 1138.4 \text{ thermal units.}$$

The evaporation that has been considered has been at a constant pressure and with a varying volume. In a boiler the evaporation must take place under the condition of constant volume. Under these circumstances the actions are not exactly the same as the ones described. Instead of the water increasing in temperature to a particular degree before evaporation commences, we have an entirely different action. The formation of steam in a closed vessel commences immediately upon the application of heat. The temperature of the water increases as the application of heat is continued, and the pressure of steam in the vessel increases as well. Consider a closed vessel to contain 1 lb. of water at a temperature of 32° F., and apply heat to the vessel until this water is entirely converted into steam. The pressure of steam in the vessel will depend upon the volume of the vessel. Assume this volume to be 5 cubic feet. Then, since the pound of water has been converted entirely into steam, the weight of a cubic foot of this steam is two tenths of a pound. From the curve for pressure and weight (Fig. 68) we note that the corresponding pressure is 84.4 lbs. per square inch. This pressure is

reckoned from vacuum and not from the pressure of the atmosphere. The pressure above the atmosphere is

$$84.4 - 14.7 = 69.7 \text{ lbs. per square inch.}$$

Now to complete our knowledge of this pound of steam it is necessary to determine the temperature of the steam as well as the total and latent heat of evaporation. From the curve of pressure and temperature we find the temperature of steam at a pressure of 84.4 lbs. per square inch to be 316° F. From the curve of pressure and thermal units in the water we find that 287 thermal units have been expended in raising the pound of water from 32° F. to 316° F. From the curve of pressure and latent heat we note that 891 thermal units have been expended in converting the water into steam. We have now complete data of the pound of steam :

Volume of steam.....	5 cu. ft.
Weight of a cubic foot.....	.2 lb.
Temperature of steam.....	316° F.
Thermal units in the water.....	287.
Latent heat of evaporation.....	{ 891 thermal units. 687,852 ft.-lbs.
Total heat of evaporation.....	{ 1178 thermal units. 909,416 ft.-lbs.

In determining the efficiency of an engine it is nec-

essary to know the pressure and weight of the steam in the cylinder at some portion of the stroke. Select a point *A* on the indicator-diagram, Fig. 69, where the valves are known to be closed. The scale of the diagram gives the pressure of steam, and the volume may be calculated from the distance through which the piston has moved and the clearance. Having now the pressure and volume of the steam, the curves Fig. 68 will give the weight and work which have been expended upon it. Part of this work is recovered, and

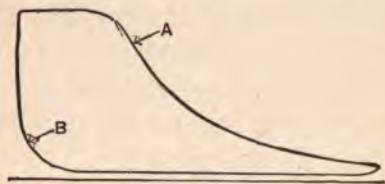


FIG. 69.

in order to determine how much select a point *B* on the compression curve. In the manner just described find the weight, etc., of the steam remaining in the cylinder at the end of the stroke. The weight of steam in the cylinder at the point *A* minus that at the point *B* gives the weight of steam used, in this end of the cylinder, per revolution.

Perhaps the calculations discussed in this chapter will be better understood by assuming the conditions of a test and making the numerical calculations.

Consider an engine having a stroke of 18 inches, and let the diameter of the cylinder be 10 inches. Let the speed be constant at 180 revolutions per minute. Let the diameter of the piston-rod be 2 inches, and the length of stroke corresponding to clearance (see page 211) be  $\frac{1}{4}$  inch. In making a test of the engine run it for 10 hours and take indicator-diagrams every 15 minutes, using a 60-lb. spring. Note very carefully the condition of the fire and the amount of water in the boiler at the beginning of the test. Weigh the coal and water used during the test, and be very careful to have the condition of the fire and amount of water in the boiler the same at the end of the test as at the beginning. Let the weight of coal used in the 10 hours be 1350 lbs., and the weight of water 9000 lbs. If the load on the engine is not constant, let the diagram Fig. 69 represent the average conditions for both ends of the cylinder.

The first operation is to calculate the engine constant:

$$\begin{aligned}
 K &= \frac{\pi(2D^3 - D_r^3)RL}{132,000} \\
 &= \frac{3.1416 [2(10)^3 - (2)^3] 180 \times 1.5}{132,000} \\
 &= 1.26.
 \end{aligned}$$

In the diagram Fig. 69 the mean effective pres-

sure is found to be 24.6 lbs. per square inch, and consequently the horse-power developed by the engine is

$$HP = 24.6 \times 126 = 31.$$

At the point *A* in the diagram the piston has advanced through .315 of its stroke or 5.67 inches, and allowing for clearance the volume of steam in the head end of the cylinder is

$$\frac{3.1416 \times 25 \times 5.92}{1728} = .29 \text{ cu. ft.}$$

The pressure of steam above the atmosphere at this point is 41.3 lbs. per square inch. This pressure being above the atmosphere, the total pressure of the steam is

$$41.3 + 14.7 = 56 \text{ lbs. per square inch.}$$

The weight of a cubic foot of steam at this pressure is (Fig. 68) .137 lb. Therefore the weight of steam in the cylinder is

$$.29 \times .137 = .0397 \text{ lb.}$$

However, all this steam is not exhausted, as part is recovered in compression. At the point *B* .0334 of the stroke or .61 inch remains uncompleted, and al-

## 226 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

lowing for clearance the volume of steam in the cylinder is

$$\frac{3.1416 \times 25 \times .86}{1728} = .039 \text{ cu. ft.}$$

The pressure of steam above the atmosphere at this point is 11.3 lb., per square inch, and the total pressure from a vacuum is

$$11.3 + 14.7 = 26 \text{ lbs.}$$

The weight of a cubic foot of steam at this pressure is (Fig. 68) .066 lb., and the weight of steam in the cylinder is

$$.039 \times .066 = .0026 \text{ lb.}$$

Therefore the weight of steam exhausted from this end of the cylinder per revolution is

$$.0397 - .0025 = .0371 \text{ lb.}$$

In a similar manner the weight of steam exhausted per revolution from the crank end of the cylinder may be calculated, remembering to deduct the volume of the piston-rod. If the conditions are the same on the two ends, the weight of steam exhausted from the crank end per revolution will be .0356 lb., and conse-

quently the total weight of steam used per revolution is

$$.0371 + .0356 = .0727.$$

The weight of steam exhausted per minute is

$$.0727 \times 180 = 13.1 \text{ lbs.,}$$

and during the ten-hour run this amounts to 7840 lbs. However, 9000 lbs. of water were fed into the boiler and 1760 lbs. remain unaccounted for. This loss is due partly to water being carried over in the steam and partly to condensation. It would evidently be unjust to charge the engine with the total amount of water fed into the boiler, and we must therefore consider 7840 lbs. as the weight of steam consumed during the run, and the remaining 1160 lbs., if charged at all, should be against the pipes. We have seen that 13.1 lbs. of steam is exhausted by the engine per minute, and this is received at the initial pressure,  $52\frac{1}{2}$  lbs. per square inch above the atmosphere or 67.2 lbs. from a vacuum. At this pressure there are (Fig. 68) 269.7 thermal units in the water and 902 thermal units latent heat. The total heat of evaporation is therefore

$$902 + 269.7 = 1171.7 \text{ thermal units.}$$

## 228 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

And since 13.1 lbs. of steam is consumed per minute, the work per minute represented by this steam is

$$1171.7 \times 13.1 = 15,349.27 \text{ thermal units,}$$

or

$$15,349.27 \times 772 = 11,849,636.44 \text{ ft.-lbs.}$$

Now since the indicated horse-power is 31, the work developed by the engine per minute is

$$33,000 \times 31 = 1,023,000 \text{ ft.-lbs.,}$$

and the ratio of actual work to the work expended upon the water is

$$\frac{1,023,000}{11,849,636} = .0845.$$

However, a perfect engine could not convert all of the energy contained in the steam into useful work. The maximum efficiency of a perfect engine is

$$\frac{T_1 - T_0}{T_1},$$

where  $T_1$  is the absolute temperature of steam on admission and  $T_0$  is the absolute temperature of the exhaust steam. The efficiency of an engine is determined by comparing its actual efficiency to this

maximum theoretical efficiency. The absolute temperature of steam is temperature indicated by a Fahrenheit thermometer plus 461.2°. The temperature of steam at admission (Fig. 68) is 300° F., and the temperature at exhaust (17.2 lbs.) is 220° F. Therefore the maximum theoretical efficiency is

$$\frac{761.2 - 681.2}{761.2} = 10.5\%.$$

Therefore the true efficiency of the engine is

$$\frac{8.45}{10.5} = 80.5\%.$$

A very common method of stating the efficiency of an engine is to say that it develops a horse-power hour for so many pounds of water. In the test under consideration the engine develops 310 horse-power hours with an expenditure of 7840 lbs. of steam, an efficiency of 25.3 lbs. of steam per horse-power hour.

It is also customary to speak of an engine as developing a horse-power hour for so many pounds of coal, though this expression necessarily includes the boiler. In the example the engine develops 310 horse-power hours with an expenditure of 1350 lbs. of coal, an efficiency of 4.35 lbs. of coal per horse-power hour.

The duty of a boiler is expressed in pounds of water evaporated per pound of coal from a tempera-

## 230 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

ture of  $212^{\circ}\text{F.}$ , and is merely the heat required for vaporization. If the evaporation occurs at any other temperature than  $212^{\circ}$  (and it always does), it must be reduced to the equivalent evaporation at that pressure. The weight of water evaporated by a definite quantity of coal varies inversely as the number of thermal units. In the problem being considered, assume the boiler pressure to be 65 lbs. per square inch above the atmosphere, and the temperature of the feed-water to be  $104^{\circ}\text{F.}$  The actual pressure above a vacuum is 79.7 lbs. per square inch. At this pressure the total heat of evaporation is 1172 thermal units. The number of thermal units contained in a pound of the feed-water, is 72. It is therefore necessary to impart

$$1172 - 72 = 1100 \text{ thermal units.}$$

Now the latent heat of evaporation at  $212^{\circ}$  is 966 thermal units, and the weight of water actually evaporated per pound of coal is

$$\frac{9000}{1350} = 6.67.$$

The equivalent evaporation at  $212^{\circ}$  is

$$\frac{1100 \times 6.67}{966} = 7.6 \text{ lbs. per pound of coal.}$$

## APPENDIX I.

### TESTS ON IRON.

WE have seen the importance of having as full information as possible concerning the relation between  $H$ , the magnetizing force,  $\mu$ , the permeability, and  $\beta$ , the induction of the iron used in the construction of dynamos and motors. The usefulness of a sample of iron depends not only on its chemical composition, but also on its physical structure and the strains to which it has been or may be subjected. It is, therefore, desirable to have the iron as pure as possible, and the work upon the metal done before the final annealing. It is not the intention here to go very deeply into the subject of magnetism, but rather to point out the methods of iron testing and give average results upon sheet, wrought, and cast iron. We have seen that the magnetizing force exerted upon a piece of iron by a current of electricity surrounding it is

$$H = \frac{4\pi nc}{l},$$

## 232 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

where  $n$  is the number of turns of wire,  $c$  the current in C. G. S. units, and  $l$  the length of the magnetic circuit in centimeters. We have also seen that

$$\mu = \frac{\beta}{H}$$

No more space need be devoted to the value of  $H$  and  $\mu$ , the quantity requiring our attention being  $\beta$ .

Two methods of determining the value of  $B$  will be considered: first, Hopkinson's method using long bars; and second, Ewing's method in which the iron is formed into rings.

Hopkinson used bars very long compared to their diameter. His arrangement is shown in Fig. 70,

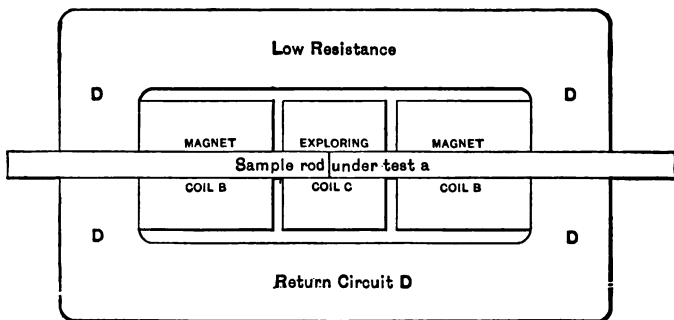


FIG. 70.

where  $aa$  is the rod to be tested,  $BB$  are two magnetizing solenoids,  $c$  is an exploring coil, and  $DD$  is a

return magnetic circuit of low resistance. The two coils  $BB$  are attached to the massive piece of wrought-iron  $DD$ . The exploring coil is not attached to the combination in any manner. When a current of electricity flows through the magnetizing coils ( $BB$ ) lines of force are set up in the rod under test. Since the rod passes through the exploring coil, this coil includes all the lines of force in the rod. The terminals of the coil are connected to a ballistic galvanometer. An elastic band or a spring is attached to the exploring coil, and when the rod is quickly withdrawn the coil is thrown across the field, the resulting elongation of the galvanometer being a measure of the induction through the rod.

Ewing follows a different method. He has the metal to be tested formed into rings or extremely long rods, in order to avoid the influence of the ends.

The ring (or rod) is wound over with many turns of small wire to serve as a magnetizing coil. There is a second coil wound as an exploring coil, the ends of which are attached to a ballistic galvanometer. When the current in the magnetizing coil is *reversed* the elongation of the ballistic is proportional to *twice* the induction through the ring.

The calibration of the ballistic may be effected by an earth coil or by the following method: On a piece of wood (or other non-magnetic material) about  $1\frac{1}{2}$  meters long and 5 centimeters in diameter wind a

single layer of wire. At the middle wind an exploring coil of about 200 turns. The permeability being unity,

$$\beta = H = \frac{4\pi NC}{10}.$$

If the elongation of the galvanometer is  $\vartheta$ ,

$$K = \frac{4\pi NC2EA}{10\vartheta};$$

where  $N$  is the number of turns per centimeter on the calibrating solenoid,  $C$  the current in amperes flowing through the primary of the solenoid, and  $K$  is the ballistic constant corresponding to this combination;  $E$  is the number of turns on the exploring coil, and  $A$  is the area of cross section in square centimeters.

Then if  $A'$  is the area of cross-section of the ring, and  $E'$  the number of turns of wire on its exploring coil, the constant of the ballistic when connected to the exploring coil of the ring under test is evidently

$$K' = \frac{4\pi NC2EA}{10\vartheta 2E'A'}.$$

This is, of course, provided the resistance of the ballistic circuit is constant. This is rarely, if ever, the case, and it is necessary to add a correction factor for the resistances.

If  $R$  is the resistance of the galvanometer circuit

when connected to the calibrating coil, and  $R'$  is the resistance when connected with the sample, the equation becomes

$$\begin{aligned} K' &= \frac{4\pi N C 2E A R'}{1092 E' A' R} \\ &= 1.26 \frac{N C E A R'}{9 E' A' R}. \end{aligned}$$

Therefore, if a deflection  $\vartheta'$  is obtained,

$$\beta = \vartheta' K';$$

$$H = \frac{4\pi N' C'}{10};$$

$$\mu = \frac{\beta}{H};$$

where  $N'$  is the number of turns per centimeter in the primary coil of the ring, and  $C'$  the current in amperes flowing through it.

If observations are taken for a number of values of  $H$ , the curves of the sample may be plotted as in Figs. 71, 72, and 73.

It is advisable to repeat the calibration of the ballistic several times in an extended test.

If the value of  $H$  be increased to any strength and then diminished to zero and increased to the same value in a reverse direction, several peculiarities will

be noticed. The value  $\beta$  will not reduce to zero when  $H$  does, but will lag behind, and will not become zero

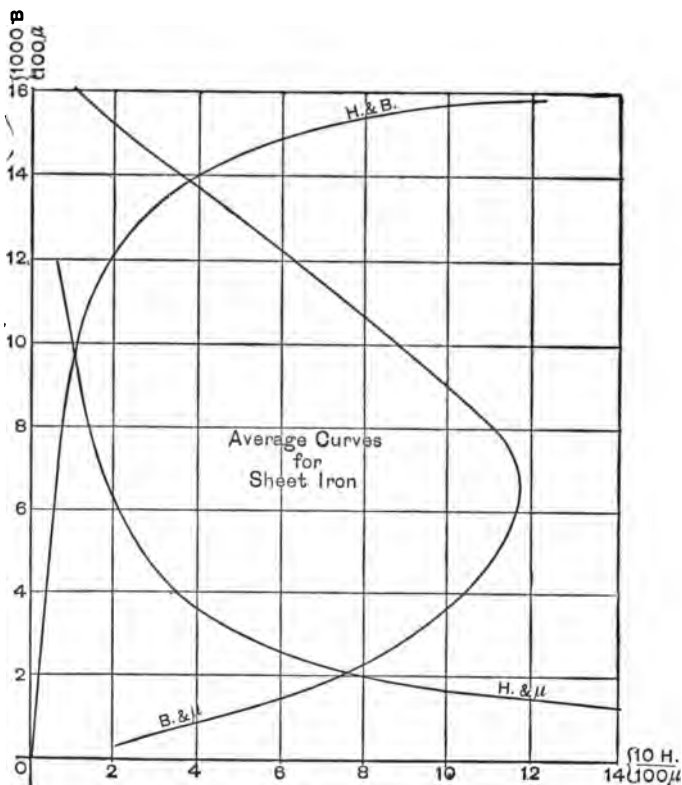


FIG. 71.

until  $H$  has reached a certain negative value. If the value  $H$  is now diminished to zero and reversed to

the original direction and increased, the same characteristics will be noticed—that  $\beta$  does not become zero

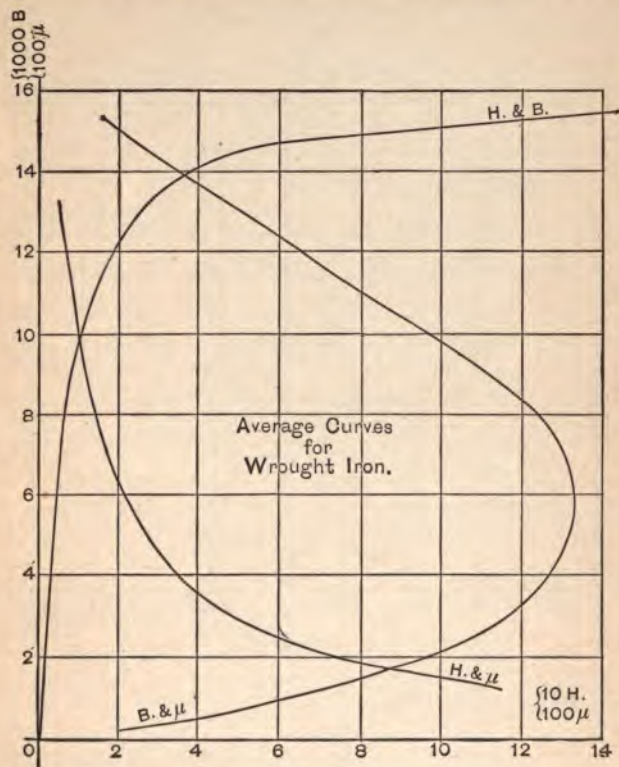


FIG. 72.

with  $H$ , but lags behind. This effect has been called Hysteresis by Prof. Ewing.

The area enclosed by the curves of increasing and diminishing magnetization is a measure of the work done in reversing the magnetism, i.e., the loss due to hysteresis.

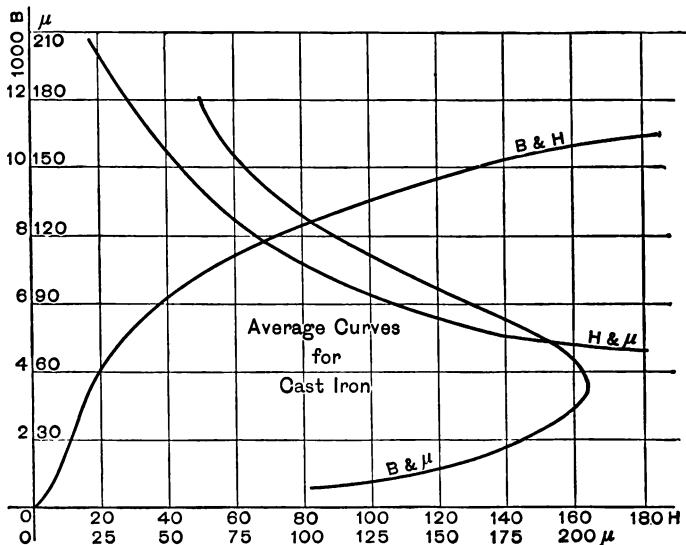


FIG. 73.

If  $\beta H$  is this area,

$$\frac{\beta H}{4\pi} = E,$$

where  $E$  is the ergs lost per cubic centimeter per cycle due to hysteresis.

Taking as an example the maximum cycle, Fig 74, the average value of  $\beta$  between a positive maximum and zero (descending magnetization) is 830. The average value from 0 to a positive maximum (ascending magnetization) is 715. Then  $830 \times 100 - 715 \times$

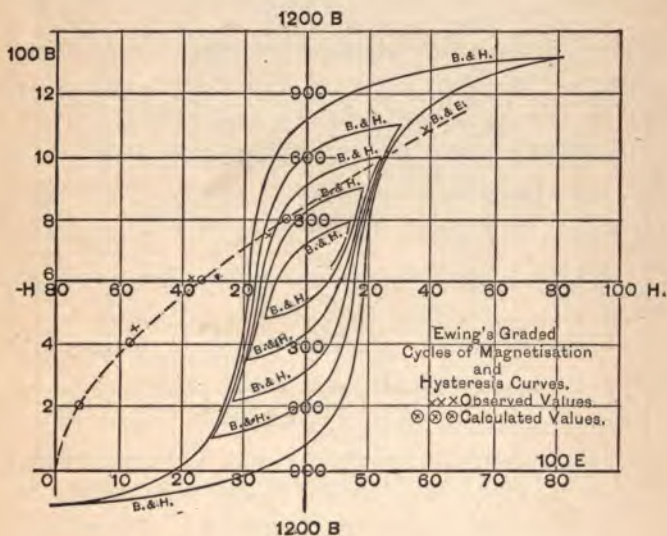


FIG. 74.

64 is one half the area. The loss in ergs per cubic centimeter per cycle is

$$\frac{(830 \times 100 - 715 \times 64) \times 2}{4\pi} = 5920.$$

## 240 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

This value is not constant, depending upon the value of  $\beta$ . The maximum value of  $\beta$  for this cycle is 1080, and at this induction only is the loss 5920 ergs per cubic centimeter per cycle. The equation of the curve connecting  $E$  and  $\beta$  is

$$E = K\beta^{1.6},$$

where  $K$  is a constant depending upon the quality of the iron. This is an empirical formula. In the curves Fig. 74, the values taken from the cycles of magnetization are marked  $\times \times \times$ , while those calculated from the above formula are marked  $\otimes \otimes \otimes$ . Their close agreement is evident. Continuing the example, we may write

$$\begin{aligned} 5920 &= K 1080^{1.6}. \\ \log K &= \log 5920 - 1.6 \log 1080 \\ \log K &= 3.4712917 \\ &\quad 4.8574781 \\ \hline \log K &= \bar{8}.6138136 \\ K &= .041 \end{aligned}$$

There is no occasion for finding the value of  $K$ , as its logarithm is the quantity used. For this particular sample we may write

$$E = .041\beta^{1.6}.$$

**A** method of determining total iron losses by

dynamometers is perhaps used more extensively than the foregoing. The connections are as shown in Fig. 75, where  $W$  is a watt dynamometer,  $N$  the resistance

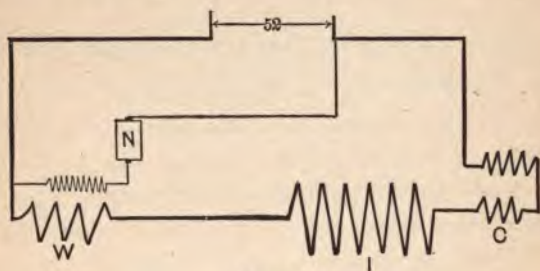


FIG. 75.

in series with its pressure coil,  $I$  is a coil of wire surrounding the sample of iron to be tested, and  $C$  is a current dynamometer.

The source of power is a transformer.

Let there be  $p$  reversals of current every per second, and  $R$  the total resistance of the circuit. Then the total power lost in the circuit is  $W$  watts. The current is  $C$  amperes and the loss due to heating of conductors is

$$C^2 R.$$

The remaining loss,  $W - C^2 R$ , must be due to iron losses. In following this method it is necessary to know the speed of the dynamo at the moment of taking the observations. If the speed of the alternator

## 242 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

is  $S$  rev. per sec. and the number of poles  $P$ , then the number of reversals of current per second is

$$p = PS,$$

and it is very desirable that this speed should be kept nearly constant.

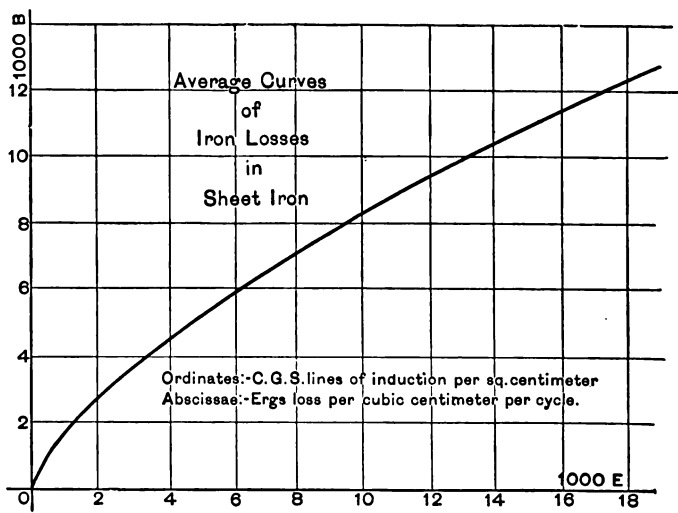


FIG. 76.

The volume of iron under test is represented by  $v$ . We may write:

$$\text{Watts lost} = W - C^2 R = (W - C^2 R) 10^7 \text{ ergs per sec.};$$

$$P = \text{cycles per second};$$

$$\frac{(W - C^2 R)10^7}{P} = \text{ergs per cycle.}$$

$$\frac{(W - C^2 R)10^7}{Pv} = \text{ergs per cu. cm. per cycle.}$$

This loss, of course, is the total iron loss, including the loss due to Foucault currents as well as hysteresis loss.

Fig. 76 gives an average curve for this loss in sheet-iron. Calculations may be greatly simplified if the speed (and consequently the cycles per second), the resistance, and the volume of iron are constant, in this the speed and volume may be combined in a constant, while the dynamometer curve can be plotted between deflections and wire losses rather than deflections and amperes.

## APPENDIX II.

### AMPERE-TURN TABLE.

THE magnetizing power of a field coil depends upon the inside and outside diameters, the size wire used and the fall of potential over the spool, and is independent of the length of spool. Provided the four factors remain constant, the strength of field is not affected by the number of fields connected in series, the ampere turns of the series being the same as of one spool having the same total fall of potential over it. This furnishes a quick method of finding the ampere turns of a given coil with any fall of potential over it.

Let  $d$  = the inside diameter (in inches) of the coil ;  
 $d_1$  = " outside " " " " " "  
 $R$  = resistance per 1000 ft. of the wire used ;  
 $E$  = fall of potential over the spool ;  
 $At$  = ampere turns.

Then the length of an average turn of wire is  $\frac{\pi \sqrt{dd_1}}{12}$

ft. and the resistance of this average turn is  $\frac{\pi R \sqrt{dd_1}}{12,000}$

ohms. Therefore, if there are  $t$  turns of wire in the coil, the total resistance of the coil is  $\frac{\pi R t \sqrt{dd_1}}{12,000}$  ohms.

The current in the coil is  $\frac{E}{\frac{\pi R t \sqrt{dd_1}}{12,000}}$  amperes, and con-

sequently we may write for the ampere turns

$$At = \frac{Et}{\frac{\pi R t \sqrt{dd_1}}{12,000}} = \frac{1}{\sqrt{dd_1}} \times \frac{12,000E}{\pi R}.$$

That is, since  $R$  depends only upon the size of wire used, with a definite inside and outside diameter of spool the magnetizing power of a coil is fixed by the size wire and fall of potential over the coil. The values of  $\frac{1200E}{\pi R}$  have been calculated for different sizes of wire and potentials and are given in the attached table. The use of this table will be best explained by an example.

Having completed a dynamo with spools 8 inches inside and 10 inches outside diameter, what size wire must be used to obtain 12,500 ampere turns from 220 volts, and how many ampere turns will result from using No. 16 wire with 110 volts?

In this case

$$\sqrt{dd_1} = \sqrt{8 \times 10} = 8.94;$$

$$\begin{aligned} K &= 8.94 \times 12,500 \\ &= 111,750, \end{aligned}$$

where  $K$  is the constant given in the table. In the column for 220 volts we find that the nearest constant to this value is  $K = 110,860$  for No. 19 wire, which gives a magnetizing force a little less than 1% too low. If it is necessary to obtain exactly 12,500 ampere turns, a combination between two different sizes of wire must be used, winding part of the spool with one size and part with the other.

If the spools are wound with No. 16 wire and the fall of potential is 110 volts, we have from the table

$$K = 104,588,$$

or

$$A_t = \frac{K}{8.94} = \frac{104,588}{8.94} = 11,700.$$

If there are four spools on the dynamo, and all are connected in series across 110 volts, the total ampere turns are 11,700. If connected in series multiple, each set has 11,700 ampere turns—a total of 23,400 ampere turns. If they are all connected in multiple, there are 11,700 ampere turns on each spool—a total of 46,800 ampere turns.

## POTENTIAL DIFFERENCE AT TERMINALS OF COILS.

Size Wire E. & S.	Volts.											
	No.	90	100	110	120	130	140	150	160	170	180	190
9	433800	482000	530200	578400	626600	674800	723000	771200	819400	867600	915800	
10	343890	382100	420310	458520	496730	534940	573150	611360	649570	687780	725990	
11	272880	303200	333520	363840	394160	424480	454800	485120	515440	545760	576080	
12	216360	240400	264440	288480	312520	336560	360600	384640	408680	432720	456760	
13	171540	190600	209660	228720	247780	266840	285900	304960	324020	343080	362140	
14	136080	151200	166320	181440	196560	211680	226800	241920	257040	272160	287280	
15	107910	119900	131890	143880	155870	167860	179850	191840	203830	215820	227810	
16	85572	95080	104588	114096	123604	133112	142620	152128	161636	171144	180652	
17	67860	75400	82940	90480	98020	105560	113100	120640	128180	135720	143260	
18	53820	59800	65780	71760	77740	83720	89700	95680	101660	107640	113620	
19	45352	50391	55430	60469	65508	70547	75586	80625	85664	90704	95743	
20	38849	37610	41371	45132	48893	52654	56415	60176	63937	67698	71459	
21	26388	29820	32802	35784	38766	41748	44730	47712	50694	53676	56658	
22	21285	23650	26015	28380	30745	33110	35475	37840	40205	42570	44935	
23	16884	18760	20636	22512	24388	26264	28140	30016	31892	33768	35644	
24	13883	14870	16357	17844	19331	20818	22305	23792	25299	26766	28253	
25	10920	11800	12980	14160	15340	16520	17700	18880	20060	21240	22420	
26	8424	9360	10296	11232	12168	13104	14040	14976	15912	16848	17784	
27	6678	7420	8162	8904	9646	10388	11130	11872	12614	13356	14098	
28	5292	5880	6468	7056	7644	8232	8820	9408	9996	10584	11172	
29	4212	4680	5148	5616	6084	6552	7020	7488	7956	8424	8892	
30	3330	3700	4070	4440	4810	5180	5550	5920	6290	6660	7030	

POTENTIAL DIFFERENCE AT TERMINALS OF COILS.

Size Wire B. & S. No.	Volts.										
	200	210	220	230	240	250	260	270	280	290	300
9	964000	1012200	1060400	1108600	1156800	1205000	1253200	1301400	1349600	1397800	1446000
10	704200	802410	840620	878830	917040	955250	993460	1031670	1069880	1108090	1146300
11	606400	636720	667040	697360	727680	758000	788320	818640	848960	879280	909600
12	480800	504840	528880	552920	576960	600900	625040	649080	673120	697160	721200
13	381200	400260	419320	438380	457440	476500	495560	514620	533680	552740	571800
14	302400	317520	332640	347760	362880	378000	393120	408240	423360	438480	453600
15	239800	251990	263780	275770	287760	299750	311740	323730	335720	347710	359700
16	190160	199668	209176	218684	228192	237700	247208	256716	266224	275732	285240
17	150800	158340	165880	173420	180960	188500	196040	203580	211120	218660	226200
18	119600	125580	131560	137540	143520	149500	155480	161460	167440	173420	179400
19	100782	105821	110860	115899	120938	125977	131017	136056	141095	146134	151173
20	75220	78981	82742	86503	90264	94025	97786	101547	105308	109069	112830
21	59640	62622	65604	68586	71568	74550	77532	80514	83496	86478	89460
22	47300	49665	52030	54395	56760	59125	61490	63855	66220	68585	70950
23	37520	39396	41272	43148	45024	46900	48776	50652	52528	54404	56280
24	29740	31227	32714	34201	35688	37175	38662	40149	41636	43123	44610
25	23600	24780	25960	27140	28320	29500	30680	31860	33040	34220	35400
26	18720	19656	20592	21528	22464	23400	24336	25272	26208	27144	28080
27	14840	15582	16324	17066	17808	18550	19292	20034	20776	21518	22260
28	11760	12348	12936	13524	14112	14700	15288	15876	16464	17052	17640
29	9360	9828	10296	10764	11232	11700	12168	12636	13104	13572	14040
30	7400	7770	8140	8510	8880	9250	9620	9990	10360	10730	11100

## POTENTIAL DIFFERENCE AT TERMINALS OF COILS.

Size Wire B. & S.	Volts.										
	310	320	330	340	350	360	370	380	390	400	410
9	1494200	1542400	1590600	1638800	1687000	1735200	1783400	1831600	1879800	1928000	1976200
10	1184510	1222720	1260930	1299140	1337350	1375560	1413770	1451980	1490190	1528400	1566610
11	939920	970240	1000560	1030880	1061200	1091520	1121840	1152160	1182480	1212800	1243120
12	745140	769280	793420	817560	841700	865840	889980	914120	938260	962400	986540
13	590860	609920	628980	648040	667100	686160	705220	724280	743340	762400	781460
14	468720	483840	498960	514080	529200	544320	559440	574560	589680	604800	619920
15	371690	383680	395670	407660	419650	431640	443630	455620	467610	479600	491590
16	294748	304256	313764	323272	332780	342288	351796	361304	370812	380320	389828
17	233740	241280	248820	256360	263900	271440	278980	286520	294060	301600	309140
18	183980	191360	197340	203320	209300	215280	221260	227240	233220	239200	245180
19	156212	161251	166290	171329	176368	181408	186447	191486	196525	201564	206603
20	116591	120352	124113	127874	131635	135396	139157	142918	146679	150440	154201
21	92442	95424	98406	101388	104370	107352	110334	113316	116298	119280	122262
22	73315	75680	78045	80410	82775	85140	87505	89870	92235	94600	96965
23	58156	60032	61908	63784	65660	67536	69412	71288	73164	75040	76916
24	46097	47584	49071	50558	52045	53532	55019	56506	57993	59480	60967
25	36580	37760	38940	40120	41300	42480	43660	44840	46020	47200	48380
26	29016	29952	30888	31824	32760	33696	34632	35568	36504	37440	38376
27	23002	23744	24486	25228	25970	26712	27454	28196	28938	29680	30422
28	18228	18816	19404	19992	20580	21168	21756	22344	22932	23520	24108
29	14508	14976	15444	15912	16380	16848	17316	17784	18252	18720	19188
30	11470	11840	12210	12580	12950	13320	13690	14060	14430	14800	15170

## 250 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

POTENTIAL DIFFERENCE AT TERMINALS OF COILS.

Size Wire B. & S.	Volts.											
	420	430	440	450	460	470	480	490	500	510	520	
9	2024400	2072600	2120800	2169000	2217200	2265400	2313600	2361800	2410000	2458200	2506400	
10	1604820	1643030	1681240	1718450	1756660	1794870	1833080	1871290	1910500	1947710	1986920	
11	1273440	1303760	1334080	1364400	1394720	1425040	1455360	1485680	1516000	1546320	1576640	
12	1009680	1039820	1069960	1091700	1115840	1139980	1164120	1188260	1212400	1236540	1260680	
13	800520	819580	838640	857700	876760	895820	914880	933940	953000	972060	991120	
14	635040	650160	665280	680400	695520	710640	725760	740880	756000	771120	786240	
15	503580	515570	527560	539550	551540	563530	575520	587510	599500	611490	623480	
16	399336	408844	418352	427860	437368	446876	456384	465892	475400	484908	494416	
17	316680	324320	331960	339600	347240	354880	362520	370160	377800	385440	393080	
18	251160	257140	263120	269100	275080	281060	287040	293020	299000	304980	310960	
19	211642	216681	221720	226759	231799	236838	241877	246916	251955	256994	262033	
20	157962	161723	165484	169245	173006	176767	180528	184289	188050	191811	195572	
21	125244	128226	131208	134190	137172	140154	143136	146118	149100	152082	155064	
22	99830	101695	104060	106425	108790	111155	113520	115885	118250	120615	122980	
23	78792	80668	82544	84420	86296	88172	90048	91924	93800	95676	97552	
24	62454	63941	65428	66915	68402	69889	71376	72863	74350	75837	77324	
25	49560	50740	51920	53100	54280	55460	56640	57820	59000	60180	61360	
26	39312	40248	41184	42120	43056	43992	44928	45864	46800	47736	48672	
27	31164	31906	32648	33390	34132	34874	35616	36358	37100	37842	38584	
28	24696	25284	25872	26460	27048	27636	28224	28812	29400	29988	30576	
29	19656	20124	20592	21060	21528	21996	22464	22932	23400	23868	24336	
30	15540	15910	16280	16650	17020	17390	17760	18130	18500	18870	19240	

## POTENTIAL DIFFERENCE AT TERMINALS OF COILS.

Size Wire B. & S.	Volts.										
	530	540	550	560	570	580	590	600	610	620	630
9	2554600	2602800	2651000	2699200	2747400	2795600	2843800	2892000	2940200	2988400	3036600
10	2024130	2063340	2100550	2139760	2176970	2216180	2255390	2292600	2330810	2369020	2407230
11	1606960	1637280	1667600	1697920	1728240	1758560	1788880	1819200	1849520	1879840	1910160
12	1274020	1298160	1322100	1346240	1370180	1394320	1418260	1442400	1466340	1490480	1514420
13	1010180	1029240	1048300	1067360	1086420	1105480	1124540	1143600	1162660	1181720	1200780
14	801360	816480	831600	846720	861840	876960	892080	907200	922320	937440	952560
15	635470	647460	659450	671440	683430	695420	707410	719400	731390	743380	755370
16	503924	513432	522940	532448	541956	551464	560972	570480	579988	589496	599004
17	399620	407160	414700	422240	429780	437320	444860	452400	459940	467480	475020
18	316940	322920	328900	334880	340860	346840	352820	358800	364780	370760	376740
19	247072	272111	277150	282190	287229	292268	297307	302346	307385	312424	317463
20	199333	203094	206855	210616	214377	218138	221899	225660	229421	233182	236943
21	158046	161028	164010	166992	169974	172956	175938	178920	181902	184884	187866
22	125345	127710	130075	132440	134805	137170	139535	141900	144265	146630	148995
23	99428	101304	103180	105056	106932	108808	110684	112560	114436	116312	118188
24	78811	80298	81785	83272	84759	86246	87733	89220	90707	92194	93681
25	62540	63720	64900	66080	67260	68440	69620	70800	71980	73160	74340
26	49608	50544	51480	52416	53352	54288	55224	56160	57096	58032	58968
27	39336	40068	40810	41552	42294	43036	43778	44520	45262	46004	46746
28	31164	31752	32340	32928	33516	34104	34692	35280	35868	36456	37044
29	24804	25272	25740	26208	26676	27144	27612	28080	28548	29016	29484
30	19610	19980	20350	20720	21090	21460	21830	22200	22570	22940	23310

## APPENDIX III.

### DETERMINATION OF THE SIZES OF WIRE FOR ARMATURES AND FIELD COILS.

IN designing a dynamo a point of considerable importance is the determination of the size wire necessary to avoid undue heating.

A well-known rule on this point is to allow 5 or 6 amperes per square millimeter for wires not exceeding 2 millimeters in diameter, and 3 amperes per square millimeter for wires which are greater in diameter. This rule does not, however, fully consider the conditions of the problem. Prof. Forbes has given the formula

$$S = 800 \frac{W}{\theta},$$

where  $S$  = radiating surface in square centimeters ;

$W$  = watts lost in heat ;

$\theta$  = maximum permissible increase of temperature in degrees centigrade.

In applying the formula to fields it may be written

$$S = 800 \frac{E^2}{\theta R},$$

where  $E$  = fall of potential over the field, and

$R$  = resistance of the coils.

In applying it to the armature, however, we must consider the total loss as  $w$ , that is, the watts lost in heating the wire by the current plus the watts lost in the armature core.

Perhaps the subject of heating effects of electric currents has never been more fully investigated than by Wm. H. Preece.\* His law is expressed in the formula

$$c = ad^{\frac{3}{2}};$$

where  $d$  = diameter of wire;

$c$  = current required to fuse it;

$a$  = a constant depending upon the material of the conductor.

Mr. Preece has proved experimentally that while this law does not hold for bare cylindrical wires of very small diameter, it becomes rigid for all diameters above 1 mm.

---

\* Elec. Eng., June 11, 1890.

The following values are given as the fusing constants for the different metals when bare and exposed in still air, the numbers giving the current in amperes required to fuse a cylindrical bar 1 centimeter in diameter, and also the fusing points in degrees centigrade.

Material.	Fusing Constant.	Fusing Temperature
Copper.....	2530	1054
Silver.....	1900	954
Aluminium.....	1873	650
German-silver.....	1292	1200
Platinum .....	1277	1775
Platinoid.....	1173	1300
Iron.....	777.4	1600
Tin.....	405.5	226
Lead.....	340.6	335
Alloy (lead 2 parts, tin 1 part)	325.5	180

The values given in the first column correspond to the constant  $a$  in the formula. We know that when the temperature of a wire carrying a current becomes stationary the rate of expenditure of energy is equal to the rate of dissipation. We know that the expenditure of energy is proportional to the square of the current flowing, and the dissipation directly proportional to the temperature of the body above the temperature of surrounding objects. This relation may be expressed by the following formula :

$$\frac{c^2}{c_1^2} = \frac{\theta}{\theta_1};$$

where  $c$  and  $c_1$  are two currents and  $\theta$  and  $\theta_1$  the corresponding temperatures. This may be written

$$c = c_1 \sqrt{\frac{\theta}{\theta_1}};$$

and if  $F$  is the fusing temperature and  $a$  the fusing constant,

$$c = a\epsilon \sqrt{\frac{\theta}{F}}.$$

The factor  $\epsilon$  may be termed the coefficient of emissivity and depends for its value upon the relative values of the radiating surfaces. A wire at a white heat will emit heat much more rapidly than one at a lower temperature. This value of  $c$  is the current required to raise the temperature of a cylindrical bar  $\theta$  degrees C. For any other size wire the formula becomes

$$cd^{\frac{3}{2}} = a\epsilon \sqrt{\frac{\theta}{F}},$$

$$d^{\frac{3}{2}} = \frac{a\epsilon \sqrt{\frac{\theta}{F}}}{c},$$

$$d = \sqrt[3]{\frac{a^2 \epsilon^2 \theta}{c^2 F}},$$

where  $d$  is the diameter of the wire in centimeters.

## 256 CONTINUOUS-CURRENT DYNAMOS AND MOTORS.

If it is desired to express the diameter in thousandths of an inch, we may write

$$d = 393.7 \sqrt{\frac{a^2 \epsilon^2 \theta}{c^2 F}}.$$

## APPENDIX IV.

### BELTING.

THERE is, probably, no subject connected with transmission of energy which is so little appreciated as that of belting. An engineer will often calculate the dimensions of a machine with extreme care and fully consider the strength of all the materials entering into its construction until he comes to the question of belting, when he will use his judgment—or, to express it more plainly, make a guess at the proper width. Nor is he altogether to blame, for an examination of the formulæ of Unwin, Nystrom, Haswell, etc., reveals the fact that they do not agree by any means. This disagreement may be attributed to two causes: first, a difference of opinion in regard to the value of the coefficient of friction; and second, the variation in tensile strength of leather.

The value of the coefficient of friction has been determined very carefully by Mr. J. H. Cromwell,\* and

---

\* See Cromwell's "Belts and Pulleys," from which the formulæ in this section are taken.

his experiments were sufficiently conclusive to be accepted.

In the tensile strength of leather there is, unfortunately, a great variation. Two strips of leather cut from the same belt may show a very marked difference in tensile strength; and so long as this want of homogeneity exists there will be an element of doubt entering in all belting calculations. It is therefore necessary to use a fairly large factor of safety. Cronwell finds the average strength of leather belts to be

950	lbs.	per	square	inch	for	single	leather	lacing ;
1000	"	"	"	"	"	"	rawhide	"
1200	"	"	"	"	"	"	double leather	"
1400	"	"	"	"	"	"	rawhide	"
1750	"	"	"	"	"	"	riveted joints ;	

and therefore considers the safe working tensions to be

325	lbs.	per	square	inch	for	single	leather	lacing
350	"	"	"	"	"	"	rawhide	"
375	"	"	"	"	"	"	double leather	"
400	"	"	"	"	"	"	rawhide	"
575	"	"	"	"	"	"	riveted joints.	

let  $T$  = tension on the tight side of the belt ;

$t$  = " " " slack " " " "

$\alpha$  = angle of smaller pulley embraced by the belt ;

$\phi$  = coefficient of friction.

Then it can be shown that

$$\log \frac{T}{t} = .00758\phi\alpha.$$

According to Cromwell's determination the value of  $\phi$  may be taken as  $\phi = .4$  for leather belts on cast-iron

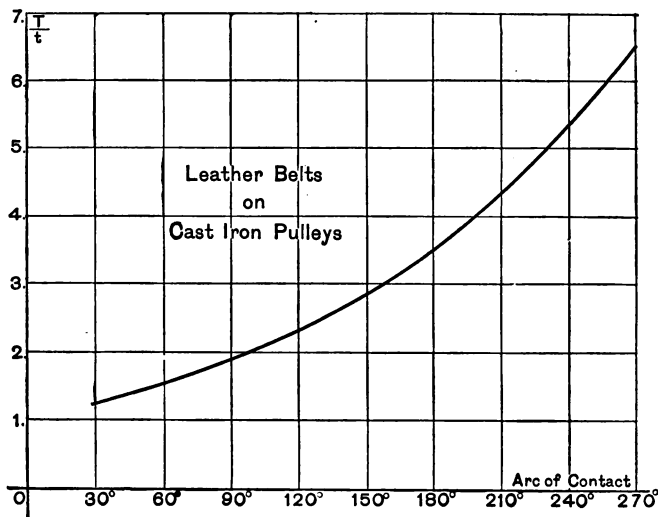


FIG. 77.

pulleys and  $\phi = .45$  for leather belts on leather-covered pulleys or rubber belts on cast-iron pulleys.

Substituting this value in the last equation,

$$\log \frac{T}{t} = .00303\alpha$$

for leather belts on cast-iron pulleys, and

$$\log \frac{T}{t} = .00341\alpha$$

for leather belts on leather-covered pulleys or rubber belts on cast-iron pulleys. The curves Figs. 77 and

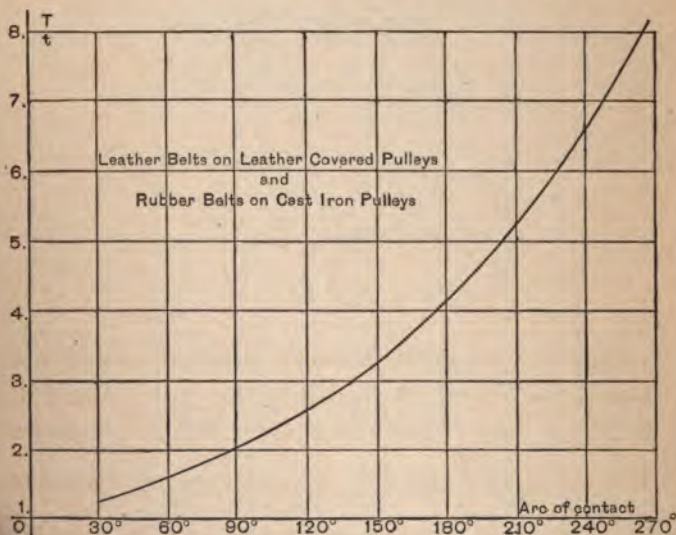


FIG. 78.

Give the values of  $\frac{T}{t}$  for the different degrees arc of on the smaller pulley.

Maximum tension on a belt is on the tight side, tension there must be sufficient to overcome

the pull at the pulley rim as well as the lesser tension on the slack side of the belt. Representing by  $P$  the pull at the pulley rim we must satisfy the equation

$$P = T - t,$$

which may be written

$$\begin{aligned} T &= P \left( 1 + \frac{t}{P} \right) \\ &= P \left( 1 + \frac{t}{T - t} \right) \\ &= P \left( \frac{\frac{T}{t}}{\frac{T}{t} - 1} \right). \end{aligned}$$

That is, in order to obtain the greatest tension on the belt it is necessary to multiply the pull at the pulley rim by a factor depending upon the arc of contact.

The values of  $\frac{T}{t}$  for any particular arc of contact may be taken from the curves Figs. 77 and 78. But since

the factor  $\frac{\frac{T}{t}}{\frac{T}{t} - 1}$  contains no variables except  $\frac{T}{t}$ , new

curves, Figs. 79 and 80 may be plotted giving directly the value of this factor.

Having determined the greatest tension on the belt, it is only necessary to divide this tension by the safe working tension of the belt (see page 258) in order to determine the proper cross section of belt. It must be borne in mind that the size belt to transmit a given power without slipping depends upon the cross-section

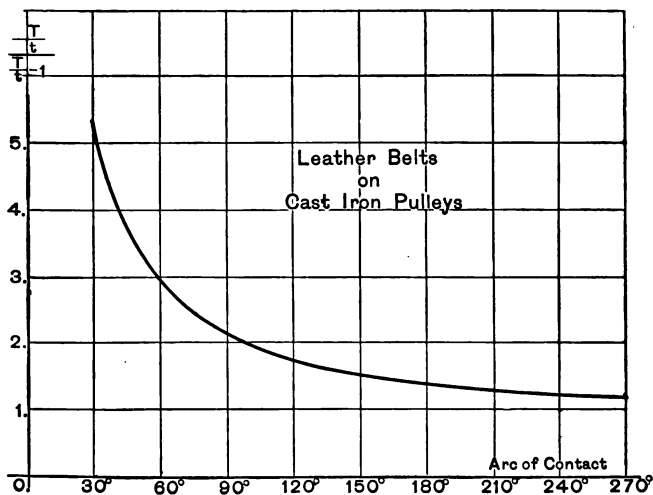


FIG. 79.

of leather and not on the width alone. That is, a belt 1 inch thick will transmit 50 per cent more power than a  $\frac{1}{4}$ -inch belt of the same width.

These belting problems may be divided into two parts: first, the determination of the necessary tension of belt required to transmit a given

power under definite conditions; second, the determination of the power which a given belt will transmit under definite conditions.

The two problems are really identical, the classification being according to the unknown quantity. The solution of belting problems is greatly facilitated by the

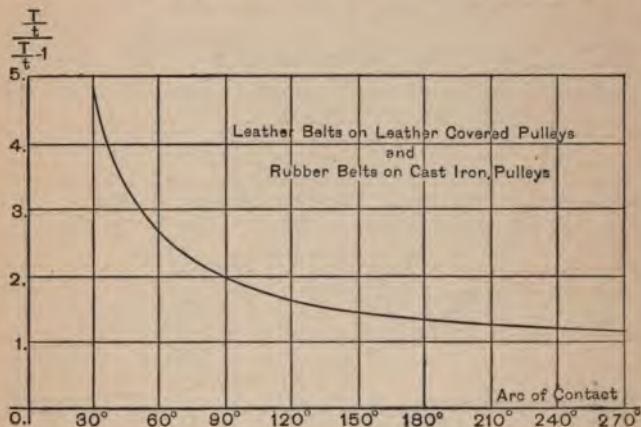


FIG. 80.

use of a set of belting curves illustrated in Figs. 81, 82, and 83. Their application may be best explained by an example.

What horse-power may be transmitted by a  $\frac{7}{32}$ -inch leather belt 4 inches wide running on cast-iron pulleys, the diameter of the smaller pulley being 8 inches and the belt embracing 90° of the pulley; the speed of the smaller pulley being 2000 revolutions per minute,

and the belt to be joined by double leather lacings?  
The cross-section of the belt is

$$\frac{7}{32} \times 4 = \frac{28}{32} = .875 \text{ square inch.}$$

Select a point on the line for double leather lacing (Fig. 82) at a distance corresponding to .875 square inch to the right of the origin.

A horizontal line through this point intersects the line for 90° arc of contact at a distance corresponding to a pull of 155 lbs. at the pulley rim. In crossing the axis it is noticed that the maximum strain on the belt is 330 lbs. In Fig. 81 select the ordinate for 2000 revolutions per minute. From its intersection with the line for an 8-inch pulley pass horizontally to the right, noting that the vertical axis is cut at a point corresponding to a belt speed of 70 feet per second. As there is no line corresponding to a pull so high as 155 lbs., it is necessary to factor this quantity. The horizontal line through 70 feet per second would cut a line for  $77\frac{1}{2}$  lbs. at a distance to the right of the origin corresponding to 9.8 H. P. There-  
e the horse-power which the belt will transmit is

$$9.8 \times 2 = 19.6 \text{ H. P.}$$

width of belt will be required to transmit 8  
r to a 6-inch pulley making 1800 revolutions  
the pulley to be covered with leather and

the belt making contact with  $150^\circ$  of the circumference? The belt is  $\frac{1}{4}$  inch thick and joined by single leather lacings. In Fig. 81 select the ordinate corresponding to 1800 revolutions per minute. From its intersection with the line for a 6-inch pulley pass horizontally to the right, noting that the belt speed is 47 feet per second. The intersection of this horizontal line with the ordinate for 8 H. P. gives a pull of 94 lbs. at the pulley rim. In Fig. 83 select the ordinate to the left of the origin corresponding to 94 lbs. pull at pulley rim. From its intersection with the line for  $150^\circ$  arc of contact pass horizontally to the right (noting that the maximum strain on the belt is 135 lbs.) to the corresponding point on the line for single leather lacing. This gives a necessary cross-section of .42 square inch. Therefore the belt width must be

$$.42 \times 4 = 1.68 \text{ inches.}$$

As the curves Figs. 81, 82, and 83 may not cover the limits required in many problems, it is sometimes necessary to use some factor of the power or belt width given in the problem. If this is done, it must be remembered to affect the result by a corresponding factor. For the convenience of those who may desire to construct a set of belting curves covering a different

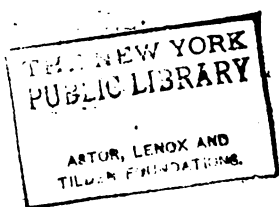
range the values of  $\frac{\frac{T}{t}}{\frac{T}{t} - 1}$  are given for the different

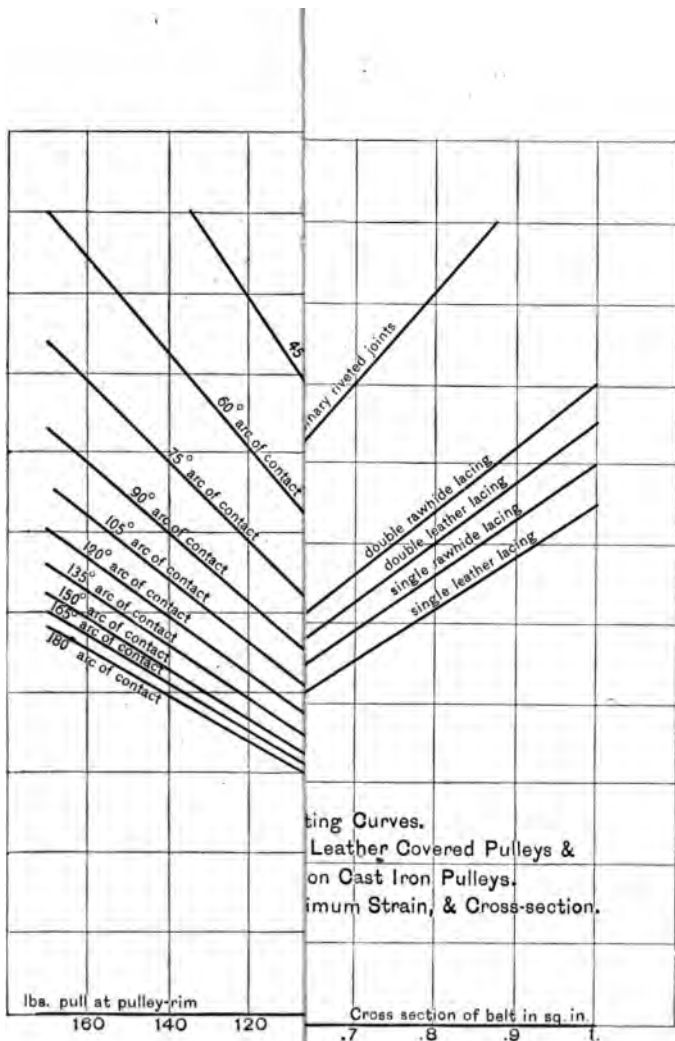
degrees arc of contact with the smaller pulley. The remainder of the data necessary for the construction of the curves requires no comment, the method of calculation being evident.

Arc of Contact in Degrees.	Value of $\frac{\frac{T}{t}}{\frac{T}{t} - 1}$	
	Fig. 82.	Fig. 83.
45.....	3.71	3.36
60.....	2.92	2.66
75.....	2.45	2.25
90.....	2.14	1.97
105.....	1.93	1.79
120.....	1.77	1.64
135.....	1.64	1.53
150.....	1.54	1.44
165.....	1.47	1.38
180. ....	1.40	1.32

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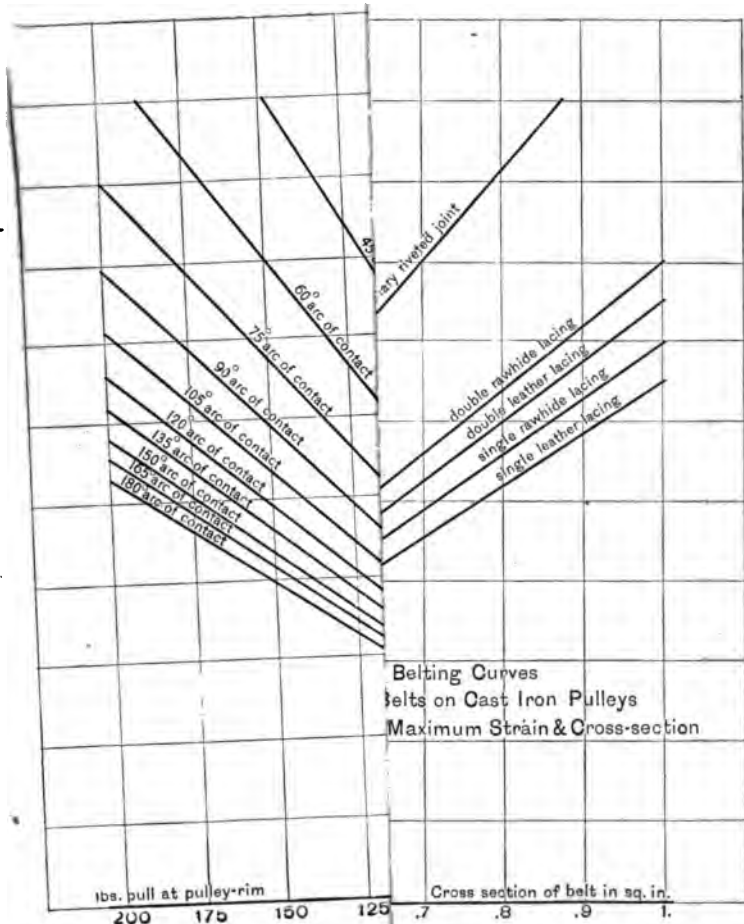
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## INDEX.

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### A

- Absorption dynamometer, 185
- Acceleration, definition of, 9
  - positive and negative, 11
- Activity, definition of, 12
  - unit of, 12
- Ampere, the, 19
- Amperes and speed, 184
  - and torque, 184
- Ampere-turns on field, 92
  - turn table, 244
- Armatures, 37
  - core losses in, 179
  - closed coil, 41
  - design of, 123
  - Gramme, 39
  - heating of, 181
  - induction in, 126
  - losses in, 130
  - open-coil, 40
  - Siemens, 38
- Armature current, effect of, 49, 56, 93
  - — in a motor, 101

### B

- Belting, 257
- Belts, arc of contact, 264
  - breaking strain, 258

- Belts, capacity of, 262
  - coefficient of friction, 259
  - safe working tensions, 258
- Boilers, duty of, 229
- Brake, Prony, 185

### C

- Capacity, unit of, 21
  - of belts, 262
- Car-motors, 116
- Cause of sparking, 51
- Centimeter, 9
- Characteristic curve, 170
- Clearance in steam-engines, 211
- Closed-coil armatures, 41
- Commutator, function of the, 30
- Compound-wound dynamos, 45, 100
  - motors, 120
- Conductors, heating of, 252
- Consequent - pole dynamo, Kapp's formula, 69
- Constant of a steam-engine, 217
- Consumption of steam in an engine, 225
- Core losses, 179
- Coulomb, the, 21
- Current, equations of, 96, 99
  - in armature, effect of, 93

Current in armature of a motor, 101

- nature of, 16
- unit of, 18

Curves, amperes, and H.P., 183

- — and speed, 184
- — and torque, 184
- characteristic, 170
- potential, 178
- saturation, 174
- speed, 177
- — and H.P., 183
- — and torque, 182

## D

Design of armatures, 123

- — field-magnets, 142
- — motors, 161

Diameter of commutation, 50

Direction of induced current, 26

- — rotation in a motor, 26

Drum armatures, 38

- — design of, 126
- — motion for steam-engine indicator, 199

Dynamo as a motor, 52

- compound-wound, 45
- consequent-pole, 47
- single magnetic circuit, 46
- series, 44
- shunt, 45
- testing, 169

Dynamometer, absorption, 185

- transmission, 186

Dyne, the, 11

Duty of boilers, 229

## E

Effect of armature-current, 49, 59, 93

Efficiency of a compound-wound dynamo, 100

- — series dynamo, 98
- — shunt dynamo, 100
- — steam-engine, 229
- test, 185
- — (electrical method), 189

Electric current, nature of, 16

Electromotive force, counter, 55

- — — definition of, 17
- — — general formula for, 90
- — — of a Gramme armature, 90
- — — — shuttle armature, 90
- — — — Siemens armature, 90
- — — unit of, 18
- — — of a 4-pole dynamo, 91

Electro-magnetic induction, 22

Elementary form of dynamo, 24

Energy, definition of, 11

Engines, clearance of, 211

- constants of, 217
- Efficiency of, 229
- H.P. of, 210

Erg, the, 12

Evaporation, total and latent heat of, 219

## F

Farad, the, 21

Field-coils, ampere-turns of, 92

Field-magnets, design of, 142

Field-magnetic, 14

- unit magnetic, 14

Force acting between two magnetic poles, 15

- lines of, 13
- tube of, 14
- unit of, 11

Foucault currents, 194

## G

Gram, the, 9

Gramme armature, 39

- — design of, 135
- — E. M.F. of, 90

## H

Heat of evaporation, total and latent, 219

Heating of armature, 181

- — conductors, 252

Horse-power of a steam-engine, 217

Hopkinson's formula for magnetic induction, 79

— method of predetermining characteristic, 70

Hysteresis, 239

— measurement of, 241

# I

Indicator-diagrams, 197, 202

— — — cramped admission, 206

— — — exhaust, 207

— — — early admission, 206

— — — excessive compression, 204

— — — late admission, 204

— — — from condensing engines, 210

— — — high-speed engines, 208

— — — theoretical expansion curve, 212

Indicator, note on attaching, 198

— reducing motion for, 199

Induced current, direction of, 26

Induction, electro-magnetic, 22

— in armatures, 126

Inertia, 11

Iron, induction in cast, 238

— — — sheet, 236

— — — wrought, 237

— losses in, 97, 130

— hysteresis, loss in, 239

— tests, 231

# J

Joule, the, 12

# K

Kapp's formula for induction, 68

— method of designing, 63

Kinetic energy, 11

# L

Latent heat of evaporation, 219

Leakage coefficient, 77

Leakage, method of measuring, 77

Length, unit of, 7

Lines of force, 13

Line integral of magnetic force, 13

Liter, the, 9

Losses in armatures, 130

# M

Magnetic circuit, Kapp method of proportioning, 63

— field, 14

— — unit, 14

— induction, Hopkinson's formula for, 79

— — Kapp's formula for, 68

— pole unit, 14

— — lines of force emanating from a, 16

— poles, force acting between two, 15

— permeability, 72

Magneto-motive force, 71

Magnets, design of field, 142

Magnetism, nature of, 12

Maximum work done by a motor, 108

Mean effective pressure, 210

Measurement of iron losses, 241

— — leakage, 77

Meter, derivation of, 7

— English equivalent, 8

Motors, armature current of, 101

— compound-wound, 120

— design of, 161

— direction of rotation of, 54, 57

— — maximum work done by, 108

— principles of, 52

— torque developed by, 104

— speed of shunt, 120

— series, 111

— shunt, 117

— street-car, 116

— starting, 59

Motors, work done by, 103  
— testing, 169

## O

Ohm, the, 19  
Ohm's law, 19  
Open-coil armatures, 40

## P

Permeability, 72  
Pole, unit magnetic, 14  
Potential curve, 178  
Potential difference, definition of, 17  
— — general formula for, 90  
— — gramme armature, 90  
— — shuttle-wound armature, 90  
— — Siemens armature, 90  
— — 4-pole dynamo, 91  
Predetermination of characteristic, 70  
Prony brake, 185  
Properties of saturated steam, 220

## R

Rectification of an alternating current, 30  
Reducing motion for steam-engine indicator, 199  
Resistance as a velocity, 20  
— unit of, 19  
Ring armatures, design of, 135

## S

Saturation curve, 174  
Saturated steam, properties of, 220  
Second, the, 9  
Series coils, determination of, 93  
— dynamo, 44, 98  
— motor, 111  
Shunt dynamo, 45, 100  
— motors, 116  
— — speed of, 120

Shuttle armatures, E. M. F., of, 90

Siemens armature, 39  
— — design of, 126  
— — E. M. F. of, 90  
Single magnetic circuit, Kapp's formula, 68  
Sparking, cause of, 51  
Speed curve, 177  
— and amperes, 183  
— and torque, 182  
— of shunt motors, 120  
Steam consumption in an engine, 225  
Steam-engines, efficiency of, 229  
— — H. P. of, 217  
— generation under constant pressure, 218  
— — — volume, 221  
Street-car motors, 116  
Symbols, table of, 61

## T

Table of symbols, 61  
Testing dynamos and motors, 169  
Tests, efficiency, 185  
Thermal unit, 218  
Time, unit of, 9  
Torque developed by a motor, 104  
Total heat of evaporation, 219  
Transmission dynamometer, 186  
Tube of force, 14  
Types of dynamos, 46  
— — motors, 55

## U

Unit of activity, 12  
— — capacity, 21  
— — current, 18  
— — force, 11  
— — heat, 218  
— — length, 7  
— — magnetic field, 14  
— — magnetic pole, 14  
— — potential difference, or E. M. F., 18

Unit of quantity of flow, 21  
— — resistance, 19  
— — time, 9  
— — weight, 9  
— — work, 12  
— — volume, 9

## V

Velocity, definition of, 9

Volume, unit of, 9  
Volt, the, 18

## W

Watt, the, 12  
Weight, unit of, 9  
Work, definition of, 11  
— done by a motor, 103  
— max. done by a motor, 108  
— unit of, 12  
— wire losses in armature, 130

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